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A Strategy for Reforming Avionics Acquisition and Support

J. R. Gebman, H. L. Shulman

40 Years
1948-1988

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During combat, high-performance avionics equipment must deliver the full extent of its designed capabilities. Failure to meet this standard is most often caused by a hard-to-find performance-degrading fault. Persistence of such faults results from weaknesses in the processes for acquisition and support of avionics. This report offers a strategy of six proposals to correct these weaknesses: (1) accelerate repair-and-maintenance-related avionics technologies, (2) improve the ability to test avionics equipment, (3) provide more complete feedback on equipment performance, (4) adopt a maintainability indicator, (5) institute maturational development, and (6) reorganize the Air Force's avionics engineering resources. Maturational development calls for government funding and direction of a special development effort aimed exclusively at repair and maintenance of the most complex avionics subsystems. Results from exploratory applications of the concept to the fire control radars on the F-15 C/D and the F-16 A/B indicate that the Air Force most needs to improve the efficient removal of performance-degrading faults.

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A Project AIR FORCE report
prepared for the
United States Air Force

X

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PREFACE

This report and its executive summary[1] explain why and how the Air Force would benefit from major changes in how it acquires and supports aviation electronics (avionics) equipment. This report describes an integrated strategy for implementing such reform, and it examines the rationale upon which the strategy is founded. The reasons for reform have been building for twenty years, as witnessed by a continuing stream of RAND research[2] all sponsored by the Air Force and often with direct special assistance from operational units.[3]

A strategy for reforming the avionics acquisition process by rearranging avionics development responsibilities was proposed in

> D. W. McIver, A. I. Robinson, and H. L. Shulman, with W. H. Ware, *Proposed Strategy for the Acquisition of Avionics Equipment*, The RAND Corporation, R-1499-PR, December 1974.

Although this strategy was partly carried out, the controversy over its main elements led the Air Force to adopt other measures, such as the 1978 creation of a Deputy for Avionics Control (DAC), with responsibility for controlling avionics acquisition but lacking direct authority over both budgeting and program management.[4]

As the DAC was being established, RAND was researching alternatives for addressing the deficiencies in the support process for the F-15's avionics equipment. Air Force actions resulting from this work included the procurement and deployment of $150 million of additional test equipment for the avionics intermediate shops, and the procurement of additional spares for the avionics.

The need for these procurements was briefed to General Alton Slay, who was then Commander of the Air Force Systems Command, during September 1979. He decided to sponsor a new RAND project on *Avionics Acquisition and Support*. This report and its companion

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[1]Gebman and Shulman, 1988.

[2]Selected reports on the early research include: Robinson and Shulman, 1967, 1972. Nelson et al., 1974.

[3]Assisting Air Force units have been stationed at such air bases as Bitburg, Cannon, Camp New Amsterdam, Hahn, Hill, Holloman, Langley, Myrtle Beach, Pease, and Plattsburg. They have operated/supported such aircraft as the F-4C, A-7D, F-111A, F-111D, FB-111, F-15A, F-15C, and F-16A.

[4]The DAC does, however, report both to the Air Force Systems Command through the Air Force Aeronautical Systems Division and to the Air Force Logistics Command; such reporting appears to be a main method for influencing avionics acquisition decisions.

executive summary constitute the final report for that project. RAND's initial charter was to assess the Air Force's progress with such measures as the DAC and to suggest further steps the Air Force might take to improve the avionics acquisition and support processes. To do so, RAND's effort initially consisted of two phases:

Phase I. Assess progress to date as manifested by the performance of fielded equipment and identify areas of needed improvement.

Phase II. Define and examine alternative ways of achieving needed improvements.

Phase I work raised serious concerns about the ability of maintenance personnel to identify and fix faults that maintenance records suggested may be persisting for weeks and even months. Phase II work led to the recommendation that the Air Force institute a special and *separate* phase of development (termed maturational development). During Stage 1 (assessment), the government would contract directly with the weapon system prime contractor, as well as *selected subsystem* contractors,[5] for four engineering services:

1. Fielding a joint team to collect detailed R&M information from one or more operational units.
2. Performing engineering analyses to define the most serious deficiencies in R&M.
3. Defining and analyzing alternatives for dealing with the most serious deficiencies.
4. Working with the government to define an appropriate and comprehensive package of improvements.

During Stage 2 (implementation) the Air Force would use the results of such services to initiate integrated improvement programs aimed at the most cost beneficial improvements.

RAND's 1980 briefing of Phase I and Phase II final results raised two controversial issues:

- What was the real condition of the sophisticated avionics equipment being used in the field?[6]

[5]Selected subsystems would be the complex types that are known to be difficult to mature (radar, weapon delivery, electronic warfare, etc.).

[6]Fire control radars on the F-15A and F-16A appeared to be experiencing serious difficulties with reliability or maintainability. All the squadrons studied had many aircraft

- Would ongoing Air Force activities make it unnecessary to invest scarce time and funds in a maturational development phase for such avionics?

The first issue was fueled by well-known problems with the accuracy of the Air Force's standard data collection systems. The second was fueled by the concerns of some that instituting a maturational development phase would be costly, could lengthen the development process, might retard the incorporation of new technologies, and could resurrect old arguments about an even larger rearrangement of responsibilities for avionics development.

During the fall of 1980, the Air Force Systems Command Directorate for Plans decided that RAND and the Air Force would undertake two measures to help resolve these issues:

- RAND would extend its research to include a Phase III that would more thoroughly research the real condition of the fielded radars with the help of information to be collected by the radar contractors.
- The F-15 and F-16 radar contractors, along with the corresponding weapon system prime contractors, would be given government funded opportunities to apply data collection and engineering analysis methods like those needed for maturational development. Within the Air Force this effort became known as the F-15/F-16 Radar R&M Improvement Program.

These two measures would provide RAND an opportunity to further assess the need for a formalized maturational development phase before publishing the project's final report.

During June of 1981, the Deputy Chief of Staff for Research, Development, and Acquisition approved the concept for the F-15/F-16 Radar R&M Improvement Program. However, the contractor teams did not start collecting data until June 1984.[7]

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with radars that required much more maintenance than other aircraft. These data (summarized in Appendix A) raised the disturbing and controversial implication that maintenance personnel could not promptly fix certain radar problems. Unfortunately, subsequent in-depth data collection and analysis by the radar contractors confirmed this implication. Section IV summarizes the contractors' findings.

[7]The chief activities that consumed the three years included: (1) coordination among Air Force organizations and review of the need for a special data collection effort (12 months), (2) preparation of a Program Management Directive (six months), and (3) the contracting process, including preparation of Requests for Proposals and negotiation of Memoranda of Understanding among the participating Air Force organizations: three System Program Offices, two Air Logistics Centers, and four air bases (18 months).

One year later the contractors presented findings and recommendations to the Aeronautical Systems Division (ASD) Strike Systems Program Office (SPO), which had been designated as the program manager for the contractor efforts.[8] The Strike SPO and the cognizant Air Logistics Centers (Ogden for the F-16 radar and Warner Robins for the F-15 radar) then briefed results and recommendations to appropriate Air Force organizations during late 1985 and early 1986.

Drawing from contractor results and the Air Force briefings, RAND completed its Phase III research during which it:

- Further assessed the condition of the subject radars as they are used in the field.
- Further assessed the need for a formalized maturational development phase during avionics acquisition.
- Considerably revised its proposed strategy for improving avionics acquisition and support.

The results of this Phase III research have been combined with pertinent results from the first two phases to produce this final report for the *Avionics Acquisition and Support* project. This report therefore summarizes results of research spanning a seven year period.

Although these results stem from research directed toward the more complex avionics subsystems for fighter airplanes, the armed services may also consider applying the resulting strategy to the acquisition and support of complex electronics in other mobile military systems such as bombers, helicopters, and tanks.

All three phases of RAND's work were accomplished within the Project AIR FORCE Resource Management Program, first under the *Avionics Acquisition and Support* project, then as a special assistance effort under the Resource Management Program's *Concept Development and Project Formulation* project, and finally under a project on *Methods and Strategies for Improving Weapon System Reliability and Maintainability*, which was sponsored by the Air Force Special Assistant for Reliability and Maintainability.

At the time of publication, several of the radar R&M improvements identified in this report have been implemented, others are under development and test, and some are planned to enter development later. Moreover, several ASD SPOs now have plans to use various adaptations of the maturational development concept in their development programs. Also, the Air Force Deputy Chief of Staff for Logistics

[8]RAND assisted the Strike SPO in defining the contractor efforts, monitoring progress, and reviewing results. The Strike SPO also hired a contractor, Support Systems Associates, Inc., to further help oversee the equipment contractor efforts.

and Engineering is reviewing a potential use of maturational development to form the backbone of component improvement programs for avionics subsystems.

SUMMARY

For combat critical avionics,[1] the Air Force continues to have problems maintaining the full measure of designed capabilities essential to sustaining combat superiority into the next century. The problems result from weaknesses in the processes that the Air Force uses to acquire and support avionics. These processes have been weakened by a rapid growth in the complexity of avionics that has been accompanied by a failure to adapt them to the growing challenges of acquiring and supporting such equipment. This report aims to stimulate consideration of a major reforming of these processes.

Section I reviews current problems of supporting modern avionics. Section II identifies the underlying weaknesses responsible for them and then describes a coherent strategy for reforming these processes. The major proposals constituting the strategy are developed in Secs. III through VI. Although these proposals are derived almost exclusively from RAND research on avionics equipment for fighter airplanes such as the F-15 and F-16, they should prove beneficial to any aircraft that rely heavily on sophisticated avionics to perform their wartime missions, and to such other mobile military systems as helicopters and tanks with complex electronics.

PROBLEMS OF SUPPORTING MODERN AVIONICS

Avionics equipment rarely experiences total failure. Rather, it typically falls victim to faults that erode its performance superiority over potential enemy weapons. When a piece of equipment fails to deliver its full measure of designed performance, the performance degradation is often subtle and difficult to observe.

Faults manifest symptoms only in specific operational modes. A subsystem with multiple modes, such as fire control radar, can have a fault that affects performance in only certain applications of particular modes. Other faults show **symptoms only in specific environments**, such as in an aircraft that is executing a violent maneuver. Thus, it is important to distinguish between faults we term *Type A* and *Type B*:

[1]The term *avionics* is used here to refer to all aviation electronics, including airborne electronic warfare equipment.

- **Type A faults have stationary observability**. They manifest symptoms that are observable no matter when or where the equipment is operated or tested. A broken picture tube in a video display is a Type A fault.
- **Type B faults have nonstationary observability**. They manifest symptoms some of the time. A faulty connection can be a Type B fault.

The current avionics acquisition and support processes concentrate mainly on Type A faults, which dominated during the early days of aviation electronics. Now, however, Type B faults dominate because greatly improved reliability has combined with larger and more highly integrated avionics systems. Type B faults seriously frustrate the identification and correction of faulty avionics equipment. Equipment with such faults all too often circulates between shop and airplane, degrading the plane's capabilities, until it either acquires a more easily observable fault or maintenance technicians set it aside for special attention.

WEAKNESSES IN THE ACQUISITION AND SUPPORT PROCESSES

The current acquisition process actually hinders the avionics developer when he attempts to solve the extraordinarily difficult engineering challenges associated with Type B faults. The main weaknesses in the acquisition process are the need for:

- Engineering data on developing technologies and equipment.
- A corporate memory for tracking conditions under which and reasons why technologies fail.
- Adequate time to develop and mature equipment.
- Information on support problems with new equipment.
- Better timing of transfer of management responsibility for equipment.

The current support process similarly hinders avionics technicians when they attempt to solve the difficult maintenance challenges associated with Type B faults. The main weaknesses in the current support process identified in Sec. II are the need for:

- Adequate information about performance degradations during routine training flights.
- A system for tracking avionics equipment performance by serial number to identify equipment with problems eluding repair efforts.

- Feedback to compensate for the use of different tests and pass/fail criteria at each maintenance level (flightline, shop, and depot).
- Capabilities for avionics technicians to repeat certain tests and initiate other tests before thermal equilibrium is achieved.
- An adequate procedure for technicians to report avionics supportability problems and recommend possible solutions.

A STRATEGY FOR REFORM

The strategy proposed for reforming avionics acquisition and support examines the major fundamental weaknesses and the most promising solutions that have come to the attention of the authors during 20 years of research in this field. Recent research has focused on avionics for such fighter airplanes as the F-15 and the F-16. The main source of data was the special data collection effort conducted during the assessment stage of the F-15/F-16 Radar R&M Improvement Program.

The two goals that guided formulation of the proposed strategy are to strengthen:

- The reliability and maintainability (R&M) of mission-essential avionics equipment already in the field.
- The development process so that future generations of mission-essential avionics equipment can more regularly deliver their full designed capabilities.

To help the Air Force achieve these goals, the recommended strategy consists of six major proposals (Fig. S.1).

Proposal 1: Accelerate R&M-Related Avionics Technologies

The first line of defense for R&M is for engineers to design it right from the outset. However, engineers' ability to do this is influenced greatly by their accumulated knowledge regarding the capabilities and limitations of the technologies used in a design. Unfortunately, to deliver a subsystem design with the specified levels of functional performance, engineers often must apply the latest advances in technology. For emerging technologies that are critical to achieving mission essential performance, it is therefore vital to accumulate a body of engineering knowledge as rapidly and as efficiently as possible to form a solid design basis. The Air Force can help strengthen the engineering knowledge available to designers by accelerating the development of

Weaknesses (Sec. II)	Proposals[a]					
	1. Accelerate R&M-related technologies (Sec. V)	2. Improve the ability to test avionics equipment (Sec. IV)	3. Provide more complete feedback on equipment performance (Sec. VI)	4. Adopt a maintainability indicator (Sec. III and IV)	5. Institute maturational development (Sec. III and IV)	6. Reorganize avionics engineering resources (Sec. VI)
Acquisition Process						
Lack of engineering data on new technologies	Strong	None	None	None	None	Strong
Insufficient corporate memory	Strong	Some	Moderate	Some	Moderate	Strong
Inadequate time to develop and mature equipment	Strong	None	None	None	Strong	Strong
Lack of information on support problems	None	Strong	Strong	Strong	Moderate	Some
Problematic timing of transfer of program responsibility	None	None	None	None	None	Strong
Support Process						
Inadequate information provided to maintenance	None	None	Strong	Strong	Moderate	Some
Ineffective indentification of unrestored equipment	None	None	Strong	None	None	Some
Insufficient flow of information between maintenance levels	None	Strong	None	Strong	None	Strong
Low maintenance capability for Type B faults	None	Strong	None	None	None	Strong
Inadequate procedures for reporting support deficiencies	None	None	Strong	Strong	None	Strong

[a]Section VII presents a detailed description for each of the recommended proposals. Further discussion of the basis for each proposal is presented in Secs. III through V, especially the sections noted within parentheses.

Fig. S.1—Applicability of proposals to weaknesses in processes for avionics acquisition and support

key avionics technologies. Certain technologies, moreover, promise especially important benefits to R&M. These need to be searched out and given appropriate emphasis. To help do this, we propose acceleration of:

- Development of selected functional performance technologies.
- Research on failure pathologies.
- Research and development of built-in test technologies.

Although the Air Force already has efforts in each of these areas, there are considerable opportunities to increase their level.

Proposal 2: Improve the Ability to Test Avionics Equipment

In the airplane, on the flightline, in the shop, and at the depot, the Air Force needs improved abilities to test avionics. Even with the best of efforts to accelerate the advancement and application of R&M technologies, faults will inevitably develop in avionics equipment. The ability to test and find faults is key to maintaining designed capabilities.

To improve the testability of avionics equipment, the Air Force can place greater emphasis on improving fault-isolation capabilities in its research and development programs and it can require specific types of improvements in test capabilities.

Proposal 3: Provide More Complete Feedback on Equipment

Even with the best of test capabilities, some faults will inevitably escape detection by ground support equipment. Thus, R&M requires that maintenance personnel have timely and reasonably complete feedback to deal quickly and effectively with faulty assets that escape repair.

To better provide such information, the Air Force can improve the quality of information received from the pilot's postflight debriefing to maintenance technicians and it can improve the technician's capability to track and identify hard-to-fix faults.

Proposal 4: Adopt a Maintainability Indicator

Even with the best of feedback to maintenance technicians about problems with equipment performance, R&M needs to attract management attention to resolve the more serious maintainability problems. Such attention is essential for identifying and fixing the underlying root causes of problems. It is also essential for effectively communicating maintainability problems to the research and development community. It is important to avoid repetition of maintainability problems in the development of new equipment.

A single measure to indicate the overall maintainability of a subsystem and its associated ground support system would be desirable. Such an indicator could:

- Complement the existing reliability indicator (MTBF)[2] and with it provide a meaningful composite picture of equipment R&M.
- Be sensitive to the full range of problems that arise in identifying faults and isolating their causes.
- Account for all flights with indications of faulty subsystem operation.

Proposal 5: Institute Maturational Development

Even with the best of implementations for the preceding proposals, some significant R&M problems will inevitably evade early, satisfactory resolution, especially Type B faults in large, complex, and tightly *integrated subsystems incorporating many new technologies.* Fire control radars for fighter airplanes fall in this category. Such subsystems and their associated ground support systems need a development phase to mature their R&M to the levels that will allow the subsystems to regularly deliver the full measure of performance for which they were designed. Such a maturational development phase needs two stages:

- Stage 1, Assessment: Collection and analysis of engineering data while the subsystem is in normal use by the operator, followed by analysis of candidate improvements and formulation of a comprehensive package of improvements[3]
- Stage 2, Implementation: Putting into operation the most cost-effective improvements that aim at regular delivery of full design performance.

Such a process offers a further line of defense that is needed to assure the delivery of necessary R&M characteristics for the most complex avionics subsystems. It would be an important supplement to the measures suggested by the foregoing proposals.

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[2]Mean Time Between Failure.

[3]Areas of needed improvement may include airborne equipment, ground support equipment, hardware, software, and maintenance procedures.

Proposal 6: Reorganize Avionics Engineering Resources

By reorganizing its avionics engineering resources, the Air Force can coordinate implementation of activities to better:

- Accelerate R&M related technologies (especially built-in test technology) to provide a better technical base for new development programs.
- Incorporate improved test capabilities in new development programs.
- Track equipment performance following repair.
- Assess maintainability needs.
- Mature equipment R&M.

In contrast to such finely tuned coordination, past avionics research and development efforts have suffered from lack of R&M guidance to laboratory projects, a potent sponsor for the advanced development of critical elements, an agency dedicated to supervising maturational development, and an agency with a robust engineering organization overseeing post-PMRT[4] maturation of both airborne and ground support equipment.

One way that the Air Force could address such deficiencies is to reorganize its avionics engineering resources in the form of an Avionics Engineering Center. Such a center would *help*[5] oversee research, development, and maturation of sophisticated avionics subsystems (fire control radars, electronic warfare systems, and the like) by

1. Sponsoring advanced development of critical elements.
2. Starting FSED early for critical subsystems.
3. Supervising maturational development for critical subsystems.
4. Overseeing post-PMRT maturation and engineering support.

In the past, there has been resistance to such concepts as an Avionics Engineering Center and subsystem-focused maturational development. Commonly cited reasons include concerns about the adequacy of the Air Force's resources that could be allocated to managing subsystem development and maturation, especially in areas with complex interfaces. Other concerns are based upon fears that the application of

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[4]Program Management Responsibility Transfers from the AF Systems Command to the AF Logistics Command when AFSC completes its management of the Full Scale Engineering Development (FSED) of the equipment.

[5]Primary responsibility for managing subsystem development may reside with a weapon system's prime contractor, *or* its System Program Office (SPO), *or* an Avionics Engineering Center. In the first two situations, the Center would assist the cognizant SPO. For further details see Sec. VI.

technological advances may be retarded, and the prime contractors' ability to optimize an overall weapon system may be seriously constrained. Against such concerns the Air Force needs to weigh the relationship between past practices and current difficulties with avionics R&M and the new challenges that will flow from the rapidly changing character of avionics technology.

CONCLUSIONS

For its combat airplanes to meet and defeat future threats, the Air Force's avionics subsystems will continue to grow in terms of functions, sophistication, and complexity, while relying heavily on the latest advances in technology. To meet the challenge of acquiring and supporting the designed capabilities of such equipment, the Air Force needs to aspire to even higher levels of excellence in avionics R&M. The Air Force would benefit from the kind of improved coordination that an Avionics Engineering Center could provide for managing the multiple lines of defense necessary for excellence in R&M. Such a center could be the capstone to a major reform built upon four cornerstone concepts:

- Explicit recognition of Type B faults
- Implementation of improved debriefing and improved tracking of equipment performance after maintenance to more rapidly identify Type B problems
- Use of fault removal efficiency as a management indicator for maintainability
- Institutionalization of maturational development as a last line of defense for R&M.

Although any of these concepts would prove beneficial, implementation of the complete strategy would constitute a major reform to how the Air Force acquires and supports avionics. With such reform, the Air Force could exploit rapidly advancing electronics technologies to help ensure the continued superiority of its combat airplanes.

ACKNOWLEDGMENTS

Over the past seven years, many people and organizations have contributed to the research described in this report. Throughout our efforts, we have received continued assistance from Headquarters United States Air Force, Headquarters Tactical Air Command, Headquarters United States Air Forces Europe, Warner Robins Air Logistics Center, Ogden Air Logistics Center, the F-15 System Program Office, the F-16 System Program Office, and the Strike Systems Program Office.

During the 1984–1985 data collection and analysis efforts, we especially benefited from the assistance of Major Rodney Fisher and Robert Benitez, the program managers for the F-15/F-16 Radar Reliability and Maintainability Improvement Program data collection and analysis phase. That phase was administered by the Aeronautical Systems Division Strike Systems Program Office, which received engineering support from Lt. Dale Evers and Robert Reed of the Air Force Acquisition Logistics Center and program technical direction support from Gary Munoz and Gene Swenson of Support Systems Associates, Inc. Charles Spruck led the Hughes Aircraft Radar Systems Group data collection and analysis for the F-15 radar, and Roy Pyle led the Westinghouse Defense and Electronics Center data collection and analysis for the F-16 radar. William McAllister led the group providing assistance from McDonnell Douglas, the prime contractor for the F-15; James Ross led the group providing assistance from General Dynamics, the prime contractor for the F-16. Participating F-15 units were the 1st Tactical Fighter Wing (TFW) at Langley Air Force Base, Virginia, and the 36th TFW at Bitburg Air Base, Federal Republic of Germany (FRG); participating F-16 units were the 50th TFW at Hahn Air Base, FRG, and the 388th TFW at Hill AFB, Utah.

Recent work on the PORTER (Performance Oriented Tracking of Equipment Repair) prototype has benefited enormously from the enthusiastic assistance of the people of the 36th TFW and the contributions of RAND colleagues Douglas McIver, Earl Gardner, and Captain Jeffrey Snyder.

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CONTENTS

FIGURES

TABLES

ABBREVIATIONS

AFB	Air Force Base
AFLC	Air Force Logistics Command
AFSC	Air Force Systems Command
AFTO	Air Force Technical Order
AIS	Avionics Intermediate Shop
ALC	Air Logistics Center
ASD	Aeronautical Systems Division
ATF	Advanced Tactical Fighter
BIT	Built-In Test
CAMS	Core Automated Maintenance System
CND	Could Not Duplicate
ECM	Electronic Counter Measures
ECS	Environmental Cooling System
EW	Electronic Warfare
FMC	Fully Mission Capable
FSED	Full-Scale Engineering Development
HUD	Head-up Display
INS	Inertial Navigation System
IOC	Initial Operational Capability
LPRF	Low Power Radio Frequency
LRU	Line Replaceable Unit
MTBF	Mean flight Time Between shop confirmed Failures
MTBI	Mean flight Time Between flights with any Indication of faults for a subsystem of interest
MTBR	Mean Time Between Removals
PC	Personal Computer
PMD	Program Management Direction
PMRT	Program Management Responsibility Transfer
PORTER	Performance Oriented Tracking of Equipment Repair
R&M	Reliability and Maintainability
SMS	Stores Management System
SPO	System Program Office
SRU	Shop Replaceable Unit
SSAI	Support Systems Associates, Inc.
TEWS	Tactical Electronic Warfare System
TFW	Tactical Fighter Wing
VHSIC	Very High Speed Integrated Circuits

I. INTRODUCTION

The next decades will see growing demands placed on pilots of combat airplanes. To acquire, track, and destroy the highest priority targets, they will need weapon systems that can sustain a margin of superiority over the equipment of prospective enemies. The Air Force long ago set a trend of relying on

- More avionics equipment,
- Greater sophistication of individual avionics subsystems, and
- Increased interdependence among avionics subsystems.

This trend unfortunately also increases the challenge of providing high reliability and easy maintenance for these avionics subsystems. The combat effectiveness of such high performance equipment is sustained only by coupling high functional performance with high reliability and ease of maintenance.

This report analyzes the reasons why the Air Force needs to make major reforms in how it acquires and supports avionics equipment. It then formulates a cohesive strategy for accomplishing such changes. Both the analysis of the current situation and the formulation of a strategy for improvement were guided by two main goals:

- To improve the reliability and maintainability of mission-essential avionics equipment already in the field so that it may more regularly deliver its designed capabilities.
- To strengthen the development process so that future generations of mission-essential avionics equipment can more regularly deliver their full designed capabilities.

CHALLENGES

The Air Force's challenge to provide high performance avionics equipment that dependably delivers the full measure of designed performance will increase simply because potential enemies, especially the Soviet Union and its allies, pose greater and greater threats. They outnumber us in military personnel and weapons. In addition, the technological sophistication and functional performance of their weapons are constantly improving.[1] Because the future will see potential enemies exploiting technological advances to enhance their war-fighting capabilities, our pilots' success in combat will continue to rely on the dependable operation of the full designed performance of all their avionics equipment.

The Air Force's challenge will also mount because future environments will probably impose stricter and stricter requirements and constraints on warfare. The Air Force may well need to deploy its combat airplanes over long distances with little or no warning. It will need combat airplanes in sufficient quantities to fight at times and places largely determined by our enemies. Therefore, the Air Force's airplanes will require great mobility and basing flexibility. Because its limited number of overseas bases will probably become increasingly vulnerable to enemy attack and rising costs will preclude prepositioning large amounts of support equipment, the Air Force will be forced to rely either on numerous airlift missions or on decreased support for its airplanes. These bases, in addition, may accommodate far fewer airplanes than an enemy might launch against them.

PROBLEMS

Our research has found that problems in supporting contemporary avionics currently pose the most serious threat to dependable delivery of full designed capabilities. Moreover, these problems stem from the weaknesses that Sec. II identifies in both the acquisition and the support processes for avionics. These findings are drawn from an assessment based upon specially collected data.

Data Source

The source is the special data collection effort conducted during the assessment stage of the F-15/F-16 Radar R&M Improvement Program. That was an exploratory application of the assessment stage for the maturational development concept described in Sec. III.

Data on the F-16 A/B radar were collected from 150 F-16s monitored during a six-month period (June-December 1984) at Hill AFB and Hahn Air Base. These data covered 16,077 flights and the resulting radar maintenance at these bases. Data were acquired by contrac-

[1]See U.S. Department of Defense, 1985; Rich, Stanley, and Anderson, 1984; Rich and Dews, 1986.

tor personnel[2] who interviewed pilots after maintenance debriefing and documented all flight anomalies observed by the pilot, including faults detected by built-in test (BIT). Contractor personnel also documented maintenance on the flightline, in the shop, and at the depot.

Similar data on the F-15 C/D radar were collected from 150 F-15s monitored during the same six-month period at Langley AFB and Bitburg Air Base. These data covered 16,702 flights and the resulting radar maintenance at these bases.[3]

An Assessment

Drawing on information from these special data collection efforts, Sec. IV shows that the main problems of supporting modern avionics are the difficulties of detecting and correcting faults in equipment. Various factors contribute to such difficulties:

- Multiple operating modes and environments.
- Limited opportunities to exercise certain subsystems.
- Rare occurrences of total failures.

Multiple Operating Modes and Environments. Sophisticated avionics equipment (such as fire control radars) operate in several modes and environments that can influence whether symptoms of a fault are observable:

- Some problems manifest symptoms in one operating mode but not in another. The pilot directly controls some radar operating modes by activating switches on the control panel, the throttle, and the stick; computers directly control other modes. In addition, the pilot often rapidly executes a series of modes (e.g., search, acquire, track, weapon release) while coping with a high workload and, in the case of fighter pilots, a physically exhausting series of maneuvers. Thus when a problem arises, the pilot may not know the operating mode. And even if he does know the operating mode, he probably cannot subsequently identify the precise settings of all switches at the time of the problem for the benefit of maintenance personnel.
- Some problems occur in one operating environment but not in another. For example, subsystems that rely on sensors (such as

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[2]The data collection team included 32 people provided by the radar contractor (Westinghouse), and four people provided by the weapon system prime contractor (General Dynamics).

[3]This effort required the fielding of a data collection team that included 36 people, 32 provided by the radar contractor (Hughes) and four provided by the weapon system prime contractor (McDonnell Aircraft).

> the antenna in a radar) for their primary source of information perform more or less well depending on the environment in which the object is sensed and on the object's movement within that environment. In addition, some problems (such as mechanical flaws in connections) are triggered by environmental changes (temperature, vibration, and deflection under high flight loads—e.g., pulling nine gs). High speed flight at low altitude especially stresses electronics because of the vibrations and high temperatures that accompany it. When a problem arises, the pilot may not know or remember all environmental conditions that influence the operation of his equipment.

Faults in sophisticated avionics subsystems often exhibit symptoms that depend on the operating mode and environment. In some operating modes and environments, the equipment may even function properly; in others, it may deliver only part of its designed performance; in yet others, it may fail completely.

Limited Opportunities to Exercise Certain Subsystems. Routine peacetime missions provide limited opportunities to fully exercise certain combat-oriented subsystems, such as fire control radars, air-to-air weapon delivery systems, and electronic warfare (EW) systems. Furthermore, routine peacetime missions may tolerate degraded capabilities that could be detrimental in combat. Thus maintenance personnel and contractors can rarely discern the full extent and effect of faults.

Rare Occurrences of Total Failures. Perhaps most important, when modern avionics fail to deliver their full measure of designed capability, the failure is usually manifested in terms of a *performance degradation* for one or more functions rather than a total loss of those functions. There are two reasons for these failures:

1. Because of the broad versatility of avionics equipment, usually some functions will work well and other functions will produce degraded levels of performance. Although a degraded condition may seem tolerable during peacetime exercises, during combat airplanes must deliver everything they were designed to do.
2. The degraded or failed performance of avionics equipment often generates intermittent symptoms, because pilots do not
   - Use identical combinations of avionics equipment on all flights,
   - Use identical modes of operation on all flights,
   - Expose avionics equipment to identical environmental and stress conditions on all flights.

In light of the problems of intermittent observability of degraded performance, maintenance technicians and R&M managers need to make a formal distinction between what we term *Type A* and *Type B* faults:

- Type A faults have what we call *stationary observability*. The processes used to observe their symptoms are inherently stationary, al' 'ays yielding the same results. Type A faults manifest symptoms that are observable no matter when or where the equipment is operated or tested. A broken picture tube in a video display is a Type A fault.
- Type B faults have what we call *nonstationary observability*. They only manifest symptoms some of the time. A loosely soldered wire can be a Type B fault. It may noticeably deteriorate a video display depending on how the radar is being used (the specific functional mode) or on how much it is jostled (the specific environments). Because of this now-you-see-it-now-you-don't quality, pilots and maintenance personnel often question whether specific Type B faults actually exist.

Because Type B faults are often difficult to define, measure, and interpret, currently used performance measures tend to presume that *all* failures of avionics equipment are Type A faults. But special data collection and analysis efforts have determined that the major weakness of avionics R&M is Type B faults: They are hard to locate and to eliminate. They pose major problems for the current support process.

MEETING THE CHALLENGES AND ADDRESSING THE PROBLEMS

The challenge before the Air Force is to provide high performance avionics that can dependably deliver the full measure of designed capabilities. To meet this challenge, the Air Force must address the serious support problems posed by avionics faults in general and Type B faults in particular. To this end we offer a six-part strategy for reforming the avionics acquisition and support processes. The first proposal addresses major weaknesses in the acquisition process contributing to support problems:

1. **Accelerate R&M Related Avionics Technologies**. The Air Force needs to speed development and maturation of technologies that promise to improve the R&M of avionics equipment.

The next three proposals address major weaknesses in both the acquisition and support processes.

2. **Improve the Ability to Test Avionics Equipment**. In the airplane, on the flightline, in the shop, and at the depot, the Air Force needs to ensure that future development efforts concentrate on isolating faults that degrade the performance of avionics equipment.
3. **Provide More Complete Feedback on Equipment Performance**. The Air Force needs to improve the quality of information received from the pilot debrief and institute serial number tracking of equipment to assist maintenance personnel in restoring subsystems to their full complement of designed capability. This information will also provide data for product improvement.
4. **Adopt a Maintainability Indicator**. The Air Force needs to adopt a maintainability indicator that measures the efficiency of the support process in removing and fixing faulty avionics equipment. It would be used in conjunction with reliability indicators to determine whether product improvement is needed.

The fifth proposal addresses a major weakness in the acquisition process, whose persistence is occasioned by insufficient feedback from the support process.

5. **Institute Maturational Development**. For selected combat-essential avionics subsystems, the Air Force needs to institute maturational development that is a multi-cycle development process, including operational tests, aimed *exclusively* at identifying and correcting fault-isolation deficiencies, failure modes, and their frequencies of occurrence in selected combat-essential and technologically sophisticated avionics subsystems.

The final proposal addresses a major weakness that limits the Air Force's ability to implement the foregoing proposals. The weakness stems from problems with the current organization of the Air Force's avionics engineering resources.

6. **Reorganize Avionics Engineering Resources**. To more closely oversee the research, development, and maturation of avionics equipment, the Air Force needs to take a fresh look at how avionics engineering management resources are organized. It should examine the alternative of instituting an Avionics Engineering Center assisted by contractor organizations.

In sum, this report recommends that sophisticated *combat-essential* avionics subsystems can benefit from increased special attention to ensure that they are reliable and easily maintained. Without a fully reliable engine, an airplane (especially a single-engine airplane) cannot safely fly; without a fully reliable combat avionics suite, a *combat* airplane cannot survive in a high-threat environment. Moreover, the sophistication of this avionics equipment is essential for these airplanes to carry out their combat missions. To tolerate less than fully mature equipment reduces the unique and necessary capabilities of these airplanes. In addition, to assure timely and fully beneficial execution of a maturational development phase, this report recommends that the Air Force formally incorporate this approach as an explicit phase within the acquisition process.

ORGANIZATION OF THIS DOCUMENT

Section II describes weaknesses in the acquisition and support processes for modern avionics that lead to the problems the Air Force encounters in supporting modern avionics. Because instituting maturational development (Proposal 5) is a key part of the strategy for reforming these processes, Sec. III describes the concept and Sec. IV describes exploratory applications of maturational development to the F-15 C/D and F-16 A/B fire control radars. Section V suggests ways of strengthening Air Force initiatives that are expected to improve avionics R&M and make maturational development more cost effective.[4] Section VI identifies further initiatives aimed at making maturational development even more cost effective. The findings from Secs. V and VI form the basis for Proposals 1 through 4, and the findings from Secs. IV through VI form the basis for Proposals 5 and 6. Section VII summarizes the recommendations and presents conclusions. Appendix A contains a preliminary assessment of avionics maturity conducted by RAND in 1980, and App. B describes how this preliminary assessment led to the exploratory applications of maturational development described in Sec. IV.

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[4]Such initiatives are sometimes viewed as competing alternatives to maturational development. The strategy put forth here views them as important complements.

II. WEAKNESSES IN THE ACQUISITION AND SUPPORT PROCESSES FOR MODERN AVIONICS

THE ACQUISITION PROCESS

In acquiring modern fighter airplanes, the Air Force must balance conflicting goals. To acquire adequate numbers of airplanes, it must hold acquisition costs to a minimum, which in turn also means holding aircraft size and weight to a minimum. However, the Air Force must also build into its airplanes avionics equipment necessary to ensure effective performance of combat missions. And such equipment inevitably adds to the cost, size, and weight of airplanes.

To balance these goals, the Air Force has increasingly relied on advancing technologies and highly integrated suites of avionics subsystems to avoid sacrificing improved functional performance for the sake of cost, size, and weight. These advancing technologies and integrated subsystems have clearly improved functional performance. They have also led to miniaturization and multifunctional use of avionics components, and increased interdependence among avionics subsystems (see Fig. 2.1).

As General Lawrence A. Skantze, Commander of the Air Force Systems Command, has pointed out, our principle has been "to take some risks, but on a prudent basis" when developing and applying advancing technologies, and we must therefore "expect some technical problems, but ones we can solve."[1] The Air Force works hard to achieve the performance edge, and it admittedly takes risks to do so.

Among the technical problems we must expect is that avionics equipment sometimes does not regularly perform at all of its designed capability.[2] That inability results from weaknesses in the ways the Air

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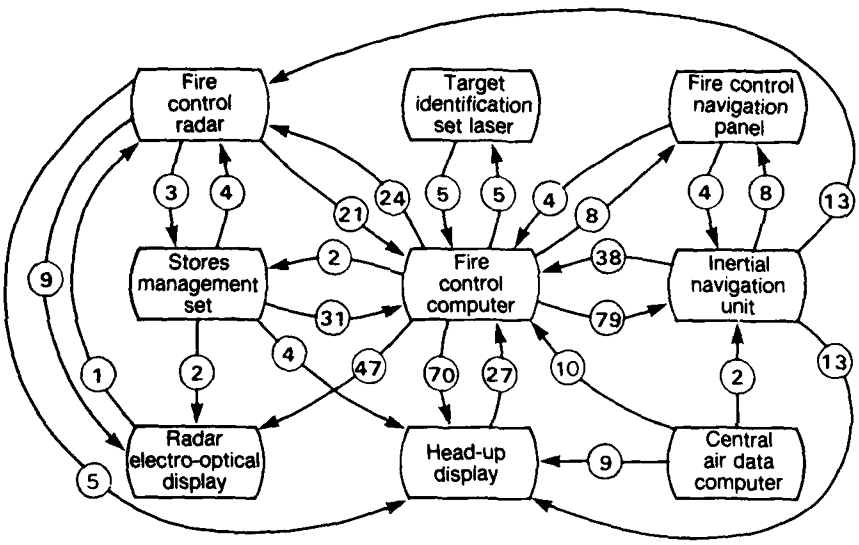
[1]Meyer and Schemmer, 1985, p. 64.

[2]For one example, the special data collection effort of the Radar R&M Improvement Program found a problem with the radar in F-16 A number 0752 that indicated prolonged degraded performance. Three days after that radar's Low Power Radio Frequency (LPRF) unit was replaced with a new one, the pilot experienced lock-on problems with the radar. Four days later, the pilot reported the radar could not pick up a tanker until it was 25 miles away; a properly functioning radar should have picked up the tanker at more than double that distance. This same radar experienced problems indicating degraded performance for the next five months. Section IV presents additional examples where persistent problems influence the deliverable performance of sophisticated avionics equipment.



Note: Numbers refer to data word types

Fig. 2.1—Complex interrelations among avionics subsystems: The number of different data words transmitted between critical subsystems for the F-16 A/B

Force acquires avionics equipment. Many problems that arise in supporting modern avionics are not foreseen during the development process and are not adequately addressed during post-development maturation because the acquisition process is not structured to deal effectively with such problems.

The Challenges of Foreseeing Problems During Development

The factors that make many support problems hard to foresee during development can be grouped in three categories:

- Equipment design
- Equipment test
- Integration of contractor efforts

Equipment Design. The avionics designer must take developing technologies and incorporate them into a large and highly integrated subsystem. He must squeeze the weight and size of this subsystem into a fighter airplane where it will be subjected to extreme temperatures and stresses as it is buffeted about the sky.

Equipment Test. The developer usually tests his subsystem on the ground in a benign environment using tests and pass/fail criteria that differ from those ultimately used in the airplane, in the airbase's avionics shop, and at the depot. All these tests differ not only because different companies build the test equipment for each maintenance level but also because the tests must become more detailed as the subsystem is disassembled at each maintenance level. These differences make it hard to demonstrate that a subsystem will pass tests when it is reassembled and reintroduced to the flight environment.

Integration of Contractor Efforts. Many companies are involved in development efforts. One company builds the airframe, another builds a specific avionics subsystem, others build subsystems that will interface with the specific avionics subsystem, and yet others build test equipment for the specific avionics subsystem. The challenge of coordinating such efforts is greatly complicated by the complex interfaces required to mechanize a highly integrated suite of avionics subsystems.

The Weaknesses in Addressing the Challenges

The acquisition process has major weaknesses when it comes to addressing hard-to-foresee support problems. The most serious fall into five categories:

- Engineering data on new technologies
- Corporate memory
- Time available for development and maturation
- Information on support problems with new equipment
- Transfer of program (including engineering) management responsibility.

Lack of Engineering Data on New Technologies. Because avionics equipment so often relies on the "cutting edge" of technology, technological developments can move rapidly from the experimental stage to application in a full-scale engineering development program. Such rapid developments limit the time that companies have to collect engineering data to support the design process. Moreover, competitive pressures make companies reluctant to share engineering data on the most promising new technologies. Consequently, engineering databases for such technologies can grow very slowly. Slow accumulation of information on failure modes and effects contributes to designs with hard-to-foresee support problems.

Insufficient Corporate Memory. Failure to accumulate and disseminate information on hard-to-foresee problems that reach the field is another weakness that contributes to current support problems. The Air Force lacks a sound vehicle for building corporate memory, in part because it typically relies on a weapon system prime contractor to manage the development and initial support for avionics subsystems.

Inadequate Time to Develop and Mature Equipment. Avionics subsystems have usually started full-scale engineering development (FSED) last, even though they are probably the most complex areas of the airplane and would benefit greatly from additional development time. The engine, another complex subsystem, typically starts FSED many years ahead of the combat avionics.[3] And the airframe typically starts FSED anywhere from six months to a year before the airframe contractor signs FSED contracts with the avionics subcontractors.

Figure 2.2 shows the major milestones in the acquisition and development of the F-15. Concept formulation for the F-15 began in June 1967, and FSED for the airframe began in January 1970. Although initial development for the engine began roughly 16 months before FSED for the airframe, FSED for the avionics systems began considerably later. FSED for the inertial navigation system (INS) began roughly eight months later, and FSED for the fire control radar system began roughly 11 months later.

Lack of Information on Support Problems. Not only do avionics developers typically lack adequate time to mature their equipment before it is delivered to operational squadrons, but shortly after fielding the initial squadron, developers lose touch with many of the operational realities in which their designs must survive. This means, for instance, that they lack engineering data on how temperatures, vibrations, and flight loads may be punishing the more fragile parts of their design. Flight testing does occur during Developmental Test and Evaluation (DT&E) and Operational Test and Evaluation (OT&E) phases, but such testing has not provided the kind of engineering assessments that are needed to address all of the R&M weaknesses.[4]

[3]Recognizing the sophisticated and *flight-essential* nature of turbine engines, the Air Force usually (1) contracts directly for their development; (2) starts this development long before that of the airframe; and (3) precedes this with many years of development, testing, and redevelopment of the engine's more critical components.

[4]Although many R&M problems are identified and addressed as a result of DT&E and OT&E, many others are not. DT&E occurs early, and involves a considerable engineering presence, but the avionics equipment often is still undergoing major modifications, the ground test equipment has not completed development, and the database (number of flights) is very small. Because OT&E occurs later, the configuration of the avionics equipment is more stable, some ground test equipment may be available, and the database is larger. However, because testing concentrates on operational evaluation rather than engineering analysis, the engineering involvement is greatly reduced from DT&E. Consequently, the resulting database often reveals only symptoms of R&M problems, and not the root causes, leading to ambiguities about whether design changes already in progress may resolve root causes. Program managers find themselves frequently tempted to take positions that the root causes are already being addressed. As Sec. IV demonstrates, too often they are not.

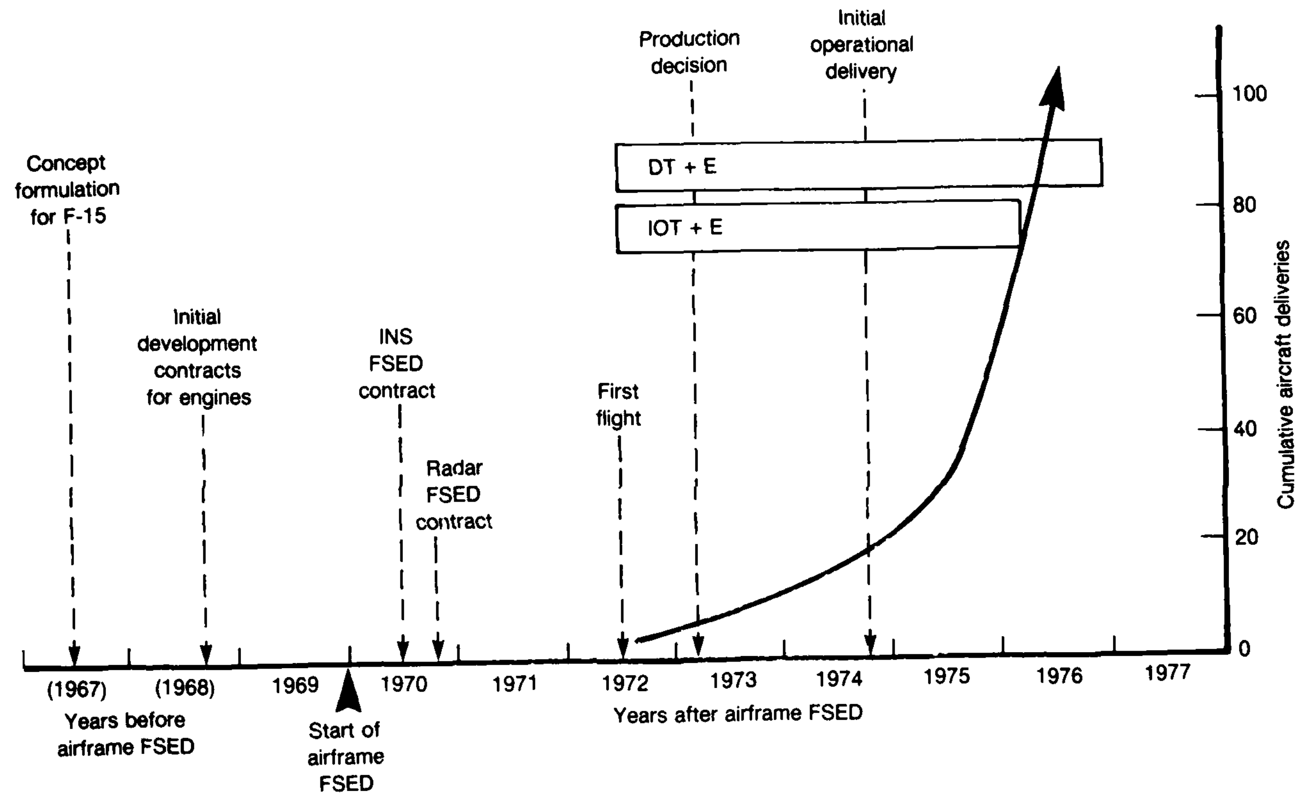


Fig. 2.2—Major milestones in the acquisition and development of the F-15

Further data collection and engineering analysis based on early operational experiences are required to build a suitably large database that reflects operational R&M problems, including the interaction between the airborne equipment and the ground-based test equipment.

Problematic Timing of Transfer of Program Management Responsibility. In the case of avionics, engineering management responsibilities are transferred from the weapon system System Program Office (SPO) to the Air Force Logistics Command (AFLC) long before the airborne equipment and its support equipment have matured to appropriate levels of R&M.[5] This transfer of engineering responsibility generally occurs during the equipment's early operational life when engineers assigned to the SPO are only beginning to have an opportunity to identify the equipment's strengths and weaknesses. Once the AFLC System Program Manager assumes responsibility, a new—and much smaller—group of Air Force engineers becomes responsible for the equipment's further maturation. These engineers must also initiate entirely new contracting documents to begin any redesign work. This is in contrast to the far simpler contracting procedure that the SPO follows to accomplish the same sort of design changes before Program Management Responsibility Transfer (PMRT). Thus, any improvements in equipment maturation slow considerably after PMRT. With an impending transfer of R&M engineering responsibilities, it is also difficult to keep the development organization interested in improving R&M.

Consequences

As a consequence of weaknesses in the acquisition process, the Air Force must often be satisfied with airborne equipment and associated support equipment that has not matured. R&M has not been developed to the point that the equipment can regularly perform at the highest level of its designed capability given available support resources. Less mature avionics equipment requires larger amounts of support; more mature avionics equipment requires smaller amounts of support. This suggests a simple tradeoff: The Air Force ought to be able to compensate for less mature avionics equipment merely by supplying additional maintenance personnel, maintenance equipment, spare parts, and the like.

[5]The appropriate level of R&M maturity will vary by subsystem and will depend upon current R&M circumstances of each development program. In each case, the probable value of a marginal increase in R&M maturity must be analyzed in light of the probable marginal cost. Identification of the most worthwhile opportunities requires a sound engineering analysis for both the current R&M situation and competing alternatives for improvement. Unfortunately, current testing (both DT&E and OT&E) often does not provide an adequate basis for such analyses.

Such a tradeoff might seem sensible *during peacetime*, especially when one considers that the maturing of avionics equipment requires the up-front expenditure of additional development time and money. However, large amounts of support are extremely expensive and can never compensate for lower levels of R&M maturity *during wartime*. Indeed, heavy wartime reliance on support decreases mobility of forces, exposes large amounts of equipment and personnel to enemy action, and places demands on scarce transportation resources; even additional support often cannot assure that the full amount of design capability has been restored.[6] In sum, heavy wartime reliance on support rather than on more mature R&M for avionics equipment unfortunately leads to lower performance than the original design of the weapon system sought.

To compound matters, even with reliance on large amounts of support equipment, weaknesses in the support process hinder the Air Force's ability to support less than fully mature avionics.

THE SUPPORT PROCESS

In supporting modern fighter airplanes, the Air Force must balance conflicting goals. To have adequate numbers of pilots trained for combat, it must sustain a certain level of training during peacetime. Likewise, to have adequate numbers of airplanes operationally ready for immediate commitment to combat during peacetime but especially during war, it must quickly complete maintenance actions. Rapid sortie generation requires trained maintenance technicians to rapidly complete maintenance actions. Thus, peacetime training needs for both pilots and maintenance technicians demand quick response by the support process. However, the Air Force must also take time to document support problems and track the adequacy of the equipment's performance.

Among the support problems we must expect is that specific items of airborne equipment will not regularly perform at the level of their designed capability and also that pilots sometimes do not report their observations of degraded performance. Neither the acquisition process nor the support process adequately addresses the difficult support problems that arise in supporting modern avionics.

[6]Section IV shows how difficult it can be to restore the full amount of designed capabilities when R&M maturity is lacking.

The Challenges Presented by Difficult Support Problems

One of the most difficult support problems is isolating a Type B fault, one that evades detection at one or more places in the support process. The avionics support processes for both the F-15 and the F-16 rely on large amounts of resources to compensate for the current maturity level of avionics equipment. Support for this equipment resides at large operating bases with complex and expensive diagnostic, support, and repair equipment. There are large supplies of spare parts and there are sophisticated facilities for repairing support materials.

Notwithstanding large investments in such materials, the support process for the F-15 and F-16 has four stages (see Fig. 2.3), during which the symptoms of a fault can evade detection:

- The cockpit
- The flightline
- The Avionics Intermediate Shop
- The depot.

The Cockpit. In the cockpit the pilot or a maintenance technician first observes symptoms of an equipment fault. Here a fault has its first opportunity to evade detection. Symptoms may be in the form of a degradation in performance detected by the pilot or indicated by the built-in test (BIT).

To help compensate for a pilot's limited ability to detect faults in sophisticated avionics equipment, airplanes employ BITs that periodically test *selected* aspects of the avionics subsystem's operation. However, the capability of contemporary BITs is limited. First, the time between tests depends on the avionics subsystem's design and the function being executed. Some functions place such heavy demands on the subsystem's computing resources that virtually no time is available to execute the BIT. Second, the BIT only indicates that avionics equipment has either passed or failed a certain test; it does not indicate gradations of passing or failing. Notwithstanding its limitations, the BIT often detects symptoms of faults that a pilot doesn't notice, sometimes because they are not yet serious problems. At other times, however, the BIT is able to detect serious problems that would become obvious to a pilot only during combat.

A further opportunity for a fault to evade detection is created by pilots' reporting practices. After each flight, the pilot assigns a performance code for each of the aircraft's major subsystems. If the pilot gives a subsystem a Code 1, maintenance personnel assume that the subsystem is performing satisfactorily for its next mission. Either a Code 2 or a Code 3 is a signal that the subsystem is not performing

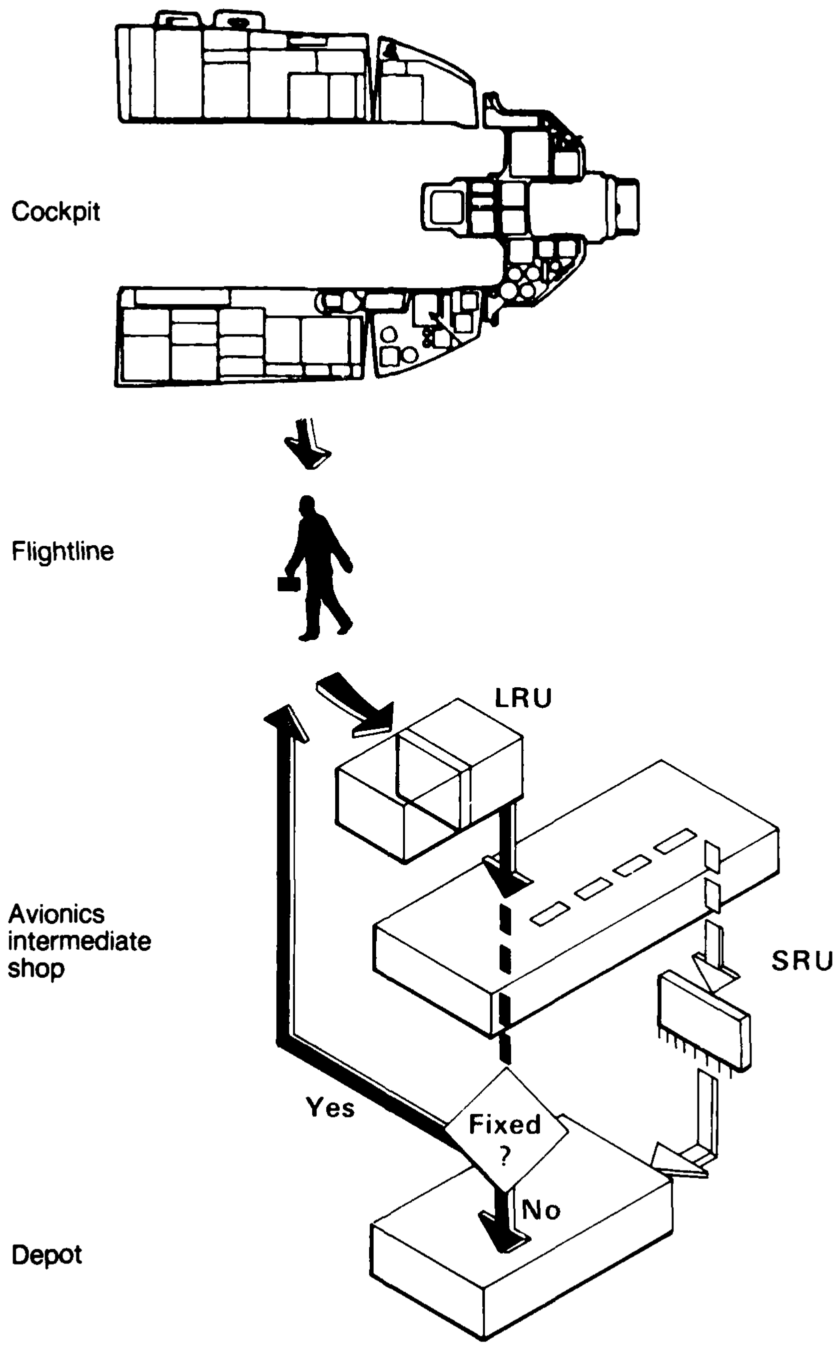


Fig. 2.3—The F-15 and F-16 avionics support process

satisfactorily. In the event of a Code 2, maintenance personnel will work on the subsystem when it is convenient to do so. One or more flights may be flown in the meantime. In the event of a Code 3, maintenance personnel will try to fix the subsystem before the airplane's next flight.

The Flightline. A fault's next opportunity to evade detection occurs during flightline maintenance. If dispatched to the flightline, the avionics specialists will attempt to stimulate symptoms or, more often, try to repeat the BIT indication, often difficult to do in the ground environment. If they can stimulate the symptoms or the BIT indications, the specialists will remove the line-replaceable unit (LRU) apparently causing the symptoms;[7] if they cannot,[8] they may either send the aircraft on its next flight or decide to investigate the claim of a fault further. If the BIT generates the reported symptoms, it also produces a coded message that sometimes helps the flightline specialists identify the faulty equipment.

The Avionics Intermediate Shop. Once specialists remove an LRU from the airplane, they replace it if possible with a spare from supply and send the suspected faulty LRU to an avionics intermediate shop (AIS) for detailed performance and diagnostic testing.[9] The next opportunity for faults to evade detection can arise from either limitations in the shop's capability or problems with the performance of its equipment.

The F-15 has over 100 avionics LRUs, and each contains a large number of shop replaceable units (SRUs), such as circuit cards. The LRU/SRU concept using the AIS was developed to avoid holding up airplanes for lengthy diagnostic tests and repairs, which are run only on LRUs that are removed from an airplane and sent to the avionics shop. Each F-15 AIS has eight types of test stations: four manual stations, which test and repair 56 LRU types; three automatic stations, which test and repair 44 LRU types; and one type of station for the tactical electronic warfare system (TEWS), which tests and repairs other LRU types.

[7]With modern avionics equipment, LRU replacement is the main type of corrective action that can be taken on the flightline. As systems age, however, wiring and connector problems account for a growing percentage of the maintenance actions. Even so, LRU replacement still remains the dominant form of corrective action.

[8]Failure to isolate can be caused by technical as well as human factors. Contributing technical factors can be deficiencies in BIT, inadequate ground support equipment, and insufficient maintenance instructions (Technical Orders).

[9]In the case of the F-15, the AIS is so large it requires at least three C-141s to deploy a single set of test equipment with its associated power generators and air conditioners. When in operation, this single set requires 4500 sq ft of floor space.

To allow one type of test station to test many types of LRUs, the AIS uses interface test adaptors for each LRU type. The AIS can test a given type of LRU, however, on only one type of test station. Moreover, a test station can test only one *type* of LRU at a time; and for a given LRU type, it can test only one *unit* at a time. Whether a shop has enough stations depends on how many LRUs require testing, the testing time for each LRU, and the availability of the test station.

The availability of test stations and their interface equipment is most strongly influenced by the availability of parts to fix the test equipment, which for the F-15 contains nearly 40,000 types of replaceable parts and assemblies. Although each part is reasonably reliable, a typical shop almost always needs replacement parts for some test stations. Shops with at least two sets of test equipment can usually maintain a capability to test and repair most LRUs, but there are times when the test equipment is unable to deliver the full amount of its designed capability.

In a sense, the shops' test equipment is similar to an airplane. The test equipment rarely quits operating. Most often, it develops a fault that degrades its test capability. Usually such a fault manifests symptoms that are detected by the test equipment's own built-in test. To avoid confusion with the aircraft's BIT, we use the term "test equipment self test" to refer to such tests. Like the aircraft, the test equipment can develop Type B faults. And as with the aircraft, correction of such faults can be a very time consuming and frustrating process. Moreover, when the test equipment self test indicates the detection of a fault, the maintenance technician usually has no other direct indication to corroborate the validity of the indication. It is not uncommon, therefore, to have Type B faults present in an item of test equipment while maintenance technicians are using the test equipment to test and repair an LRU. Such a fault in test equipment can create an opportunity for a fault in an LRU to evade detection.

Thus, in the shop, there are two basic ways that a fault can evade the attention of maintenance technicians:

- Technicians fail to stimulate and detect symptoms of the fault.
- Technicians succeed in detecting symptoms of the fault but fail to isolate the cause.

Failure to detect or isolate can be caused by technical as well as human factors. Contributing technical factors include:

- Test equipment (along with associated software and Technical Orders) not designed to detect or isolate the fault.
- Test equipment not performing up to its designed capabilities.

Human factors can include the training, skill, and experience of the technician. These factors can be especially important because the technician is also responsible for most of the tests and repairs directed at the test equipment.

Section IV shows that the technical factors are the major source of difficulty because fault detection and isolation by the shop is based upon tests and pass-or-fail criteria different from those used by the BIT on the airplane. Consequently, its tests can find discrepancies that are completely unrelated to the problem encountered on the airplane. Although shop technicians may believe that they have restored the full performance for and item of equipment, the equipment may still possess the fault detected on the airplane.

The Depot. If a shop cannot repair an LRU, it sends that item to a depot for further testing. The depot has the same types of stations as those in the shop. It also has additional equipment that can test and repair SRUs within LRUs.

Diagnosis and repair of SRUs by the depot is complicated by the fact that its test stations, like those in the shop, use measurements different from those used by the BIT on the airplane. In addition, its equipment for testing SRUs uses measurements different from those used elsewhere in the support system.

In the depot, a fault can evade the attention of maintenance technicians in the same basic ways as at the shop; contributing technical and human factors are also the same.

Weaknesses in Addressing the Challenges

From the cockpit through the depot major challenges confront the capability of the support process to deal with difficult faults. Moreover, the support process has major weaknesses in its ability to address the challenges of efficiently detecting Type B faults. The most serious weaknesses fall into five categories:

- Information provided to maintenance concerning inflight symptoms of degraded performance.
- Identification of equipment that has not been fully restored to deliver its designed capabilities.
- Flow of information between maintenance levels.
- Maintenance capability to detect and isolate Type B faults in the shop and in the depot.
- Procedure for reporting support deficiencies and possible solutions.

Inadequate Information Provided to Maintenance. Because there are so many opportunities for Type B faults to evade detection and isolation during the maintenance process, pilots must inform maintenance of all indications of potential problems with equipment performance, especially after the completion of a maintenance action. The pilot needs to report all symptoms, whether pilot observations or BIT-detected faults, at the post-flight maintenance debriefing. The lack of a consistent practice in this regard is a fundamental weakness of the current support process. Frequently, maintenance lacks adequate information about avionics equipment performance during routine training flights. Pilot-observed indications of faults often go unreported to technicians even when the BIT corroborates degradation in the equipment's performance.

Ineffective Identification of Unrestored Equipment. Even when a pilot fully reports all inflight indications of potential problems, a systematic process is necessary for integrating such information with information from the maintenance process to quickly identify equipment that the maintenance process has failed to restore to its designed capability. The current support process lacks an effective way to track avionics equipment performance by serial number. Such a capability could facilitate the identification and repair of faulty units that repeatedly circulate between shops and airplanes.[10]

Insufficient Flow of Information Between Maintenance Levels. Even with full reporting by pilots, and even with an effective way to track equipment by serial number, a further link is required for the fully effective flow of information essential for quickly identifying equipment with hard-to-fix faults. This last link is a mechanism for translating test results from one level to another. Currently, maintenance technicians in the avionics shop cannot use information from the aircraft-level BIT to either guide or verify their own tests. Similarly, maintenance technicians in the depot cannot use information from either the shop-level tests or the aircraft-level BIT. Such communication barriers create a major weakness in the support process. Shop or depot-level technicians can find and correct out-of-tolerance conditions that are totally unrelated to the inflight fault, but nothing may be done to correct the inflight fault. Shop or depot technicians believe that their work has fixed the equipment when in fact their actions are irrelevant to the condition that caused the equipment to be placed in the maintenance process.[11]

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[10]Such capability is needed for both LRUs and SRUs.

[11]For the F-15 radar database discussed in Sec. IV, 20 percent of the LRUs sent to the shop fell into this category.

Low Maintenance Capability for Type B Faults. Appropriate remediation of all of the foregoing weaknesses would only improve the ability to more quickly *identify* specific equipments with hard-to-fix faults. To actually *repair* the equipment, special tests and even additional test resources may be required. Two major weaknesses exist. First, most LRU tests that are conducted with automatic test equipment have limited flexibility. Technicians cannot break into the lengthy test sequence to repetitively run a block of tests in an area where a Type B fault may reside. Moreover, the test sequence usually must start at a fixed point. The unit of equipment under test will therefore achieve a thermal equilibrium long before most of the tests are executed, making it difficult to find thermally sensitive faults. A second weakness is the lack of capability to control the environment for the unit of equipment under test. Unfortunately, many Type B faults are sensitive to flight-environment. Environmental chambers, while not practical for airbase-level avionics shops, could be installed at depot test facilities to provide some capability to represent the flight environment (both thermal and vibration aspects).

Inadequate Procedures for Reporting Support Deficiencies. Finally, it is reasonable to expect deficiencies in the support process for large, complex subsystems that rely on leading edge advances in technology for much of their important capabilities. Deficiencies can be expected with tests at all levels (BIT, shop, and depot), with test equipment (shop and depot) maintenance, and with maintenance instructions (Technical Orders) at all levels. But, even with such expectations, the support process lacks an effective and efficient mechanism for gathering feedback from maintenance technicians.

Consequences

As a consequence of weaknesses in the support process, the Air Force must often be satisfied with equipment that is delivering less than the full measure of what it was designed to do. Although such equipment usually can perform mission-essential functions, the question is how well would the host weapon system fare against the front-line equipment of a sophisticated adversary? A radar that can dependably find targets at its full design range is clearly preferable to one that, although still functioning, is seriously degraded in detection capability. The degree of functional degradation often does not make much difference during peacetime training flights, but it can make a crucial difference in combat. Weaknesses in the support process, therefore, pose a very insidious threat to sustaining combat superiority.

III. THE CONCEPT OF MATURATIONAL DEVELOPMENT

This section describes the observations that led to the formulation of the concept of maturational development. It then defines the proposed concept and suggests some areas where implementation would be most beneficial. Finally, it addresses some concerns regarding the concept's practicality.

OBSERVATIONS

Formulation of the concept of maturational development was strongly influenced by two classes of observations. The first is a set of specific observations drawn from two development programs from the 1960s. The second is a set of general observations drawn from a combination of those experiences from the 1960s and twenty years of subsequent RAND research on avionics acquisition and support.

Specific Observations

During the 1960s, two development programs were especially noteworthy for making impressive improvements in reliability after the initial fielding of equipment:

- Minuteman I guidance subsystem
- Carousel inertial navigation subsystem

Each program required the application of the most recent advances in technology to what were, at the time, very complex subsystems. Although these subsystems differ from modern avionics in both technologies and complexity, we can draw important lessons from the processes used to improve their reliability.

Minuteman Guidance Subsystem. In developing the missile guidance subsystem for Minuteman I, the Air Force aimed at achieving a high mean time between removal (MTBR). When it went into initial operating capability (IOC), Minuteman I had an MTBR of 600 hours.[1] Although this would be good for an avionics LRU, it was unacceptable

[1]Information about the Minuteman I program is drawn from the personal files of H. L. Shulman, who participated in the Air Force's reliability growth program for the guidance subsystem.

for the Minuteman, which should operate continuously (more than 8700 hours per year) to be ready for immediate firing. With this MTBR of 600 hours, the Air Force had to remove each Minuteman's inertial guidance equipment from the silo and send it to the repair facility at Newark, Ohio, on an average of once every 25 days. Each time this occurred, the missile was out of service for roughly seven days because of the time required to remove the guidance system and to replace it with one that had to be warmed up and calibrated. Even if the Air Force had unlimited spare guidance subsystems, about one-fourth of its missiles would be unavailable at any given time. And spares were in short supply, so many more missiles were unavailable. This extremely serious availability problem caused the Air Force to initiate a second development effort aimed exclusively at reliability improvement. That effort achieved an MTBR of 9000 hours and allowed the average Minuteman I to stay in the field for over a year. Though this second development effort cost an additional $150 million, in the long run it saved some $1.5 billion, but much more important, it increased the availability level of the missile force from 70 percent to over 95 percent.[2]

Carousel Inertial Navigation Subsystem. In developing its Carousel inertial navigation subsystem for transport airplanes, General Motors found that it had to use three development efforts.[3] After some preliminary development work for the Air Force with no major concern for MTBR, General Motors signed a contract with commercial airlines guaranteeing an MTBR of 1500 hours. It then developed and produced a model that achieved an MTBR of only 100 hours. Consequently, General Motors instituted a second formal development effort, including production and operation, that yielded an MTBR of between 500 and 600 hours. Still failing to live up to its contractual obligation, General Motors instituted a third development effort aimed exclusively at reliability improvement. That effort actually did achieve an MTBR of 1500 hours. The three development efforts cost roughly $50 million in then-current dollars.

Although having to operate under more demanding conditions than either the Minuteman guidance systems or the Carousel inertial navigation subsystems, the F-15's inertial navigation subsystem went

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[2]Cost estimates are expressed in then-year dollars.

[3]Information about the Carousel program is drawn from the personal files of H. L. Shulman, who was responsible for the initial development of Carousel while he was Director of Research and Development at the A.C. Spark Plug Division of General Motors Corporation.

through only one development cycle, yielding an MTBR of 75 hours.[4] The total RDT&E cost for the subsystem was $7.6 million in then-current dollars. We believe the F-15's inertial navigation system would be considerably more reliable had it been subjected to the same kind of rigorous and recursive testing and redesign.

General Observations

We made certain general observations in 1980, based upon the foregoing experiences and twenty years of assisting the Air Force on a variety of ad hoc avionics projects such as:

- F-4 inertial navigation reliability improvement
- F-4 inertial navigation support
- F-111D BIT improvement program
- FB-111 inertial navigation/Kalman filter problem
- F-16 avionics development
- F-15 avionics support

The general observations are:

1. Without special data collection efforts, engineers have lacked data about actual operational experience, and developers have been hindered in identifying the most serious problems that have plagued performance and support of electronic subsystems. Moreover, too often engineering information has not focused on combat-relevant functions and has not taken into account the multiple functions of subsystems, the multiple operating states for each function, and complex integrations among subsystems.

2. Avionics acquisition programs have overemphasized speed of development. Much can and should undoubtedly be done to remove many of the bureaucratic inefficiencies that currently slow down the acquisition process. We cannot fight enemies with weapons that are still on the drawing boards. But an undue emphasis on speed of development has lead to a failure to

- Collect accurate and relevant data concerning potential problems with sustaining a weapon system's designed performance.

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[4]The F-15's inertial navigation system must, for example, withstand repeated high-g environments and must function properly in spite of short warmup periods. Although all inertial guidance navigation subsystems are extremely sensitive to changes in temperature, these changes are especially serious in combat airplanes, which must be able to scramble with short warning. By contrast, the inertial guidance in the Minuteman operates continuously, and thus has no need for short warmup; and the inertial navigation subsystems in transports can usually be warmed up adequately before the transport needs to take off.

- Redesign portions of the weapon system and its support system to avoid these problems

When fielding new weapon systems, we have been preoccupied with the time to IOC and have largely ignored time to *matured* operational capability. The latter can take much longer, as can be seen in the time needed to introduce radar R&M improvements for the F-15 and F-16 (see Sec. IV).

CONCEPT

Drawing upon the very positive experience of the Minuteman I guidance and the Carousel navigation programs and a series of ad hoc avionics projects over the years, we proposed the following concept for maturational development during 1980.

Shortly after introducing the first 24 to 72 units of a new subsystem to an operational environment, a new phase of full-scale engineering development would commence. This new phase, known as the maturational development phase, would consist of two stages:

- Assessment of R&M situation.
- Implementation of improvements.

Stage 1: Assessment of R&M Situation

The objective of stage 1 is for equipment contractors to work with the government in a team effort to define a comprehensive package of R&M improvements that addresses the most serious R&M deficiencies in:

- The subsystem of interest.
- The interfaces among the subsystem of interest, the host weapon system, and related subsystems.
- The support process at all levels (cockpit, flightline, shop, and depot) for the subsystem of interest. This includes tests, test equipment, and maintenance instructions (TOs).

Accomplishment of the objective requires four major activities, each requiring considerable involvement by equipment contractors:

1. Collect data based on operational experience to determine where, how, how often, and why a combat-essential avionics subsystem fails to deliver the full amount of its designed capability.

2. Analyze the data to identify the most serious deficiencies in terms of the effect on dependable delivery of the subsystem's designed capability.
3. Define candidate actions to correct or remediate the most serious deficiencies and analyze the prospective cost and benefits.
4. Work with the government to define a comprehensive package of actions to improve the R&M situation for the subsystem of interest.

Data Collection. Three critical considerations are the nature of the data to be collected, who collects the data, and the size of the database.

Data must be sufficient to allow personnel to assess the effectiveness of each maintenance action based upon tracking operational performance after the completion of maintenance. To do this:

- Data on all indications of potential problems must be collected at the pilot's maintenance debriefing.
- Data on all maintenance actions must be collected at the flightline, the shop, and the depot.

Only the equipment contractors have the engineering expertise and knowledge of the equipment essential to the design of R&M improvements. To assure that appropriate data are acquired to support their analysis and subsequent redesign efforts the equipment contractors must field and manage the data collection team.

The database must be large enough to capture a statistically meaningful sample for the most serious R&M deficiencies. Adequate data samples are essential to understanding which deficiencies are most prevalent. One way to gauge the necessary size for the database for a subsystem of interest is to consider the average number of flights between visits to the depot for the types of equipment (SRU or LRU) that most frequently go to the depot. For such equipment, it is desirable to have at least 20 visits in order to sort out the dominant failure modes. For example, say that a subsystem has SRUs that, on average, visit the depot no more than once every 300 flights for any given type. This number is representative for complex subsystems. Then, with our assumptions, the database should be based on at least 6000 flights just to have a good sample for the SRUs that failed most frequently. To gain statistically meaningful insight into other SRUs it is probably prudent to double or triple this figure. Thus, for modern avionics, our sense is that a database should cover from 12,000 to 18,000 flights.

Analysis. A critical consideration here is the measures used to characterize R&M deficiencies. Currently, mean time between failures

(MTBF) is the most widely accepted measure of reliability. For avionics, MTBF translates into mean flying hours between failures confirmed by the avionics shop. MTBF data unfortunately fail to capture the entire R&M picture because they do not reflect occasions when:

- The pilot does not report discrepancies.
- The pilot detects something wrong with avionics equipment, but maintenance personnel do not remove an LRU from the airplane.
- The BIT indicates something wrong with avionics equipment, but maintenance personnel do not remove an LRU from the airplane.
- Maintenance personnel remove an LRU from the airplane but cannot find anything wrong with it in the shop.

To arrive at a much more complete view of the R&M picture, we need to recognize that R&M is a quality with multiple dimensions. Moreover, because precision becomes increasingly more difficult as the complexity of the equipment grows, we can only devise indicators that capture the salient features of the R&M quality being sought. In view of these limitations, we suggest a more complete assessment of R&M that includes both MTBF and *fault removal efficiency*. To estimate the fault removal efficiency, we need both MTBF and the mean time between indications (MTBI) of faults perceived by the pilot and by the BIT.

To arrive at a meaningful MTBI for *current* aircraft, pilots need to report all indications of suspected faults, maintenance personnel need to maintain a historical record of all pilot-reported faults for each aircraft, and the Air Force needs to select aircraft randomly for those rare opportunities when air-to-air weapons are fired and ECM equipment is employed. Moreover, to arrive at a meaningful MTBI for *future* aircraft, the BIT should capture and report information about operating modes (such as switch settings) and operating environments (such as temperature of equipment) whenever the BIT detects a fault.

If all indications are reported, differences between MTBI and MTBF reflect difficulties in locating and correcting faults in avionics equipment. We propose the following avionics maintainability indicator:

$$\begin{array}{c}\text{Fault}\\ \text{Removal}\\ \text{Efficiency}\end{array} = \frac{\text{MTBI}}{\text{MTBF}} \times 100$$

where MTBI = Mean Time Between flights with one or more Indications of faulty operation of the avionics subsystem.

MTBF = Mean Time Between flights with a shop-confirmed Failure of the avionics subsystem.

A low indicator means that maintenance personnel can rarely find a confirmed failure for flights when one or more faults were indicated. This points toward problems in one or more of the avionics subsystem, the BIT, the shop/depot tests/equipment, the TOs, and maintenance personnel training.

Such an avionics maintainability indicator will identify those subsystems that experience the most difficulty in meeting their designed capability and that impose the greatest demands on the support process. Subsystems that experience especially great problems are lacking in maturity: They and their associated support process have not experienced enough engineering development to regularly deliver their full measure of designed capability within the current support structure. The data collection and analysis activities, including the application of this maintainability indicator, point to the areas in most need of improvement.[5]

Candidate Improvements. To identify the most appropriate ways to achieve needed improvements, the equipment contractors may need to review whether certain materials should be changed, certain components should be derated, and other components should be redesigned. In addition, they may have to consider imposing tighter quality control on certain materials and production methods. To improve maintainability, the contractors may have to change the BIT circuitry and programs, the system partitionings, and the test points. In addition, they may have to add test points and capture more information about the airplane's mode of use at the time of degraded performance. All of this should occur not only at the subsystem and LRU level (involving the subsystem contractor) but also at the weapon-system level (involving the prime contractor) when the equipment is installed and tested in a flight vehicle.

[5]If there are many false indications (e.g., because of a bad BIT) then the fault removal efficiency will have a low value. By improving the BIT so as to reduce the number of false indications, the contractor can raise the fault removal efficiency for his subsystem. This parameter intentionally penalizes a bad BIT because it undermines maintainability.

Improvement Package. The last activity for Stage 1 is the formulation and coordination of a proposed R&M improvement package through these organizations. Formulation of a cohesive and comprehensive package of improvements will often require the cooperation of the subsystem contractor, the shop test equipment contractor, the depot test equipment contractor(s), and the host weapon system contractor. It will also require the cooperative efforts of the System Program Office for the host weapon system, the Air Logistics Center for the subsystem of interest, and the Air Logistics Center for the test equipment.

Stage 2: Implementation of Improvements

Stage 2 of maturational development involves carrying out the improvements, some of which can be expected to require further development efforts.

Without such further development, engineers cannot accurately assess where, how, how often, or why many Type A and Type B failures will occur in avionics subsystems. This is true for several reasons: Their design methods and tools simply cannot predict all important causes and modes of failures; they lack complete information about new materials and processes needed to manufacture avionics subsystems; and they cannot foresee all environments in which the avionics subsystems will perform and all complex interrelations among them.

Developers therefore need to conduct a development effort, including data collection and operational tests, at least once to discover where, how, how often, and why a subsystem will fail (see Fig. 3.1). After identifying these failures, developers must then repeat a portion of the engineering development effort if they are to reduce failure rates and improve maintainability.

IMPLEMENTATION OF MATURATIONAL DEVELOPMENT

The experiences of the Air Force with its Minuteman missile guidance subsystem and of General Motors with its Carousel inertial navigation subsystem for transports suggest that a maturational development process can achieve dramatic improvements. Inertial guidance or navigation subsystems on missiles, transports, and tactical fighters share similar basic components: accelerometers, gyros, and electronics. In addition, they share similar problems with their reliability and

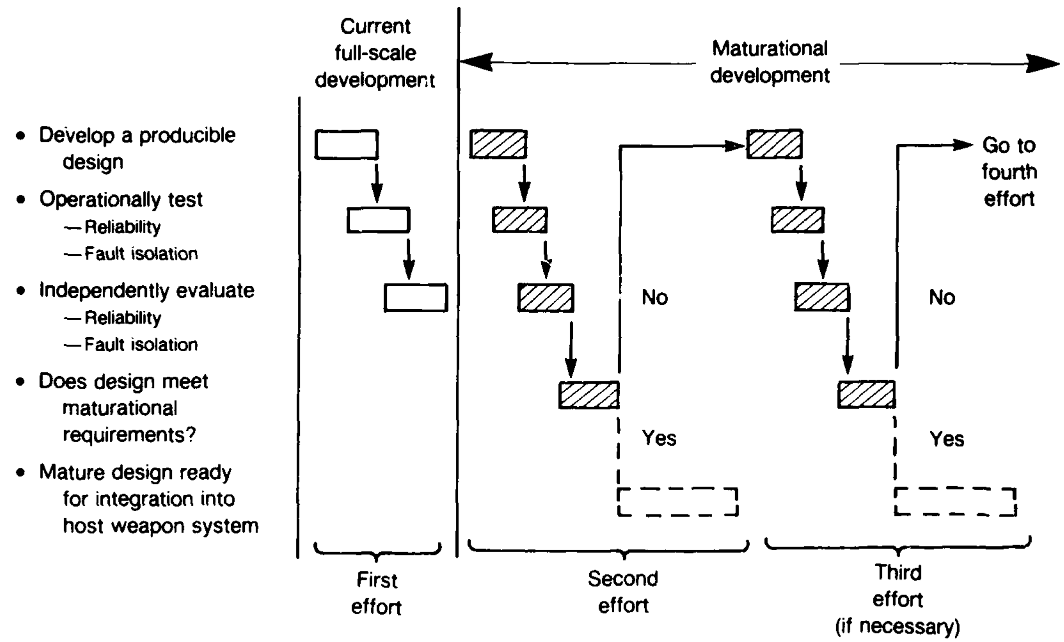

Fig. 3.1—Maturational development: A multiple phase process

maintainability. However, tactical fighters must operate in much more demanding environments. We recommend a formal maturational development phase for three classes of complex combat-essential avionics subsystems:

- New subsystems that are just beginning development.
- Existing subsystems that are being modified to improve their functional performance.
- Existing subsystems in which improvements in reliability and maintainability would considerably narrow the gap between designed and operationally available performance.

Maturational development can achieve the largest benefit-to-cost ratio when aimed at developing selected new avionics subsystems that are just beginning development. In such cases, it should occur *prior to high-rate production* to avoid the high costs of retrofitting hardware. For this class of equipment, the Air Force might most profitably begin with new avionics for the next generation of tactical fighters.

In addition, a maturational development phase can greatly improve selected existing avionics equipment whenever it receives large *performance-oriented* improvements. Existing equipment can most benefit from maturational development when its improvements:

- Involve large changes.
- Affect the weapon system's overall design.
- Increase the airplane's modes of operation.
- Raise performance specifications considerably for existing modes.
- Make a large proportion of its components no longer interchangeable with those of the previous model.

With this class of equipment, the Air Force should especially consider instituting maturational development for

- Fire control radars, such as
  - APG 68 for the F-16 C/D.
  - APG 70 for the F-15 E.
- Electronic counter measures equipment such as
  - Internal countermeasures set for the F-15.
  - Threat warning system for the F-16.
  - Advanced self-protection jamming system for the F-16.
  - Jamming pods (ALQ-131 Block 2 and ALQ-184) for the F-4 and the F-111.
- Improved weapon delivery systems for the F-15 and F-16.
- New low altitude night targeting infrared (LANTIRN) navigation and targeting pods.

Finally, a maturational development effort can also help address reliability and maintainability problems experienced by equipment already in the field. For this class of equipment, the Air Force has already begun addressing currently fielded models of the fire control radars in both the F-15 C/D and the F-16 A/B (see Sec. IV).

Maturational development can lead to both mid-term and long-term improvements. For the mid-term, it can help reduce the adverse effects of problems with R&M on combat effectiveness. For the long term, it can help avoid these problems before the Air Force adds new avionics equipment to future tactical airplanes.

CONCERNS AND SEARCHES FOR ALTERNATIVES

Since the concept of a formal maturational development phase was proposed in 1980, concerns about its practicality have stimulated a search for alternatives. Four classes of concerns have emerged:

- Cost.
- Schedule.
- Program survival.
- Management of subsystem development.

Cost

The concept of maturational development does call for additional investment by the government during both Stage 1 and Stage 2. Such additional investment needs to be weighed against the prospective benefits delivered by more mature subsystems and a more mature support process. Because of the cost, maturational development should be selectively applied—both in terms of the subsystems selected and the timing of subsystem development. Because the costs of retrofitting hardware can be the dominant expense in a maturational development program (as demonstrated in Sec. IV), maturational development promises to be most beneficial when Stage 1 (Assessment) can be completed very easily during the production run. Starting Stage 1 shortly after IOC would help reduce costs, as would stretching out the production run. Another cost-saving tactic would be to develop subsystems for application to multiple weapon systems where practical. The maturation cost would thereby be amortized across a broader production base.

Stretching out production raises other concerns, such as increased program cost due to the stretch and delaying the introduction of new capabilities. The benefits of stretching production will depend upon the nature of the subsystem development program and the development program for the host weapon system.

Schedule

The maturational development concept does not have to influence development schedules for either subsystems or host weapon systems, unless the government makes the judgment that it would be wise to start subsystem development early or stretch production. Presumably, a decision to do so would be based upon a balanced consideration of both the prospective benefits and the costs[6] of such a choice. Here the central question would be whether it is worth starting a little sooner (or waiting a little longer) to obtain a more mature subsystem and a more mature support process.

Of course, starting development sooner has another hidden opportunity cost in that an earlier start on design implies an earlier freeze on the technology base to be incorporated in the design. Here the choice is between a somewhat newer technology and a less mature subsystem and a somewhat older technology and a more mature subsystem. Such difficult choices would need to be carefully considered for each major subsystem that would be a candidate for maturational development.

Program Survival

Regardless of whether maturational development is scheduled in a way that influences a subsystem (or weapon system) acquisition schedule, there is a concern that planning the funds and designating milestones for a maturational development phase will raise eyebrows and jeopardize the survival of a program. For maturational development to be accepted and practiced effectively, a new mindset will be required throughout all levels of the acquisition process. The explicitly planned incorporation of a maturational development phase, with healthy funding plans for both Stage 1 and Stage 2, should be viewed as a sign of a healthy program. Development programs that cannot afford to conduct a healthy maturational development phase should be carefully reconsidered.

[6]Costs, of course, would include both fiscal expenses and the opportunity cost of delayed fielding of equipment.

Subsystem Development

For the past three decades the Air Force has relied heavily on each weapon system's prime contractor to oversee and manage the development of the complex and critical subsystems used in its weapon system. Because the Air Force has not had much recent experience in managing the development of complex avionics subsystems, there is a concern that it would have neither the resources nor the experience to adequately perform this critical function.

A further concern is that government's management of subsystem development would limit the ability of a prime contractor to optimize the overall performance of the weapon system. If, for example, a fire control radar was government-furnished equipment, then the prime contractor would be stuck with the general arrangement of the subsystem and would not be free to explore tradeoffs in terms of the packaging and placement of the equipment.

The concept of maturational development does not necessarily require the government to manage subsystem development, which would clearly have certain costs. Such costs and the prospective benefits would need to be carefully weighed.

Searches for Alternatives

The foregoing concerns have prompted searches for a more satisfactory alternative to maturational development. Attention has have directed toward three areas:

- Existing maintenance data.
- Warranties.
- Requirements and testing.

Recent RAND research has identified numerous ways that the Air Force can work toward strengthening its activities in each of these areas.[7] However, even when strengthened, such activities only partly address the weaknesses that maturational development strives to remedy.

Existing Maintenance Data. Although the Air Force can learn more from the maintenance data that it routinely collects,[8] the limited depth of that data renders it insufficient for resolving root causes of R&M deficiencies for complex avionics. It can help identify problem areas, but it fails to provide the detail necessary for engineering

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[7]Petruschell, Smith, and Kirkwood, 1987; Stanley and Birkler, 1986; Stucker and Smith, 1987.

[8]See, for example, Stucker and Smith, 1987.

analysis, especially for Type B faults. Such analysis is essential to assessing the full scope and effect of R&M problems, as well as to understanding root causes. Although the symptoms of R&M problems discussed in Sec. IV were also evident in the Air Force's maintenance data, there was great ambiguity about underlying causes[9] until the engineering databases and engineering analyses were completed.

Warranties. Application of warranties to the acquisition of weapon systems became mandatory during 1984–1985. The most beneficial role and probable contributions of such warranties is a subject in need of further study. The general types of information that the Air Force needs to collect to support such research has been identified.[10]

Analysis of the limited information that is available for pre-1985 warranties "suggested that at least four factors contribute positively to warranty success:

- Specific, easily measurable objectives;
- Simple, explicit contractor incentives and remedies;
- Simple, explicit government duties; and
- Reasonable prices and expectations."[11]

It is difficult to extrapolate the ultimately most desirable role of warranties from this initial assessment. The apparent message, however, is to keep things simple and explicit. This indication raises some early warning signs for complex avionics equipment. The complexities of both the airborne equipment and its associated support process create reasonable doubts about whether the Air Force can devise an adequate set of simple measures that would provide explicit contractor incentives, while delineating explicit government duties.

Unfortunately, the fault-removal-efficiency measure, introduced previously in this section, does not appear to satisfy these guidelines. Not only is the value for this measure influenced by the performance of various contractors and various government agencies, but sorting out the probable contributions of each contractor or agency can require a cooperative engineering effort.[12] It seems to us that future research on warranties should devise sets of measures and approaches to warranties that are conducive to such cooperation.

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[9]Consequently, for both radars there was much disagreement about responsibility for the root causes. For example, frequent removal of one type of LRU was claimed to be due to poor troubleshooting and problems in other parts of the airplane. Only the contractor's engineering analysis finally adjudicated this issue. (See Sec. IV.)

[10]See Stucker and Smith, 1987.

[11]Ibid., p. vi.

[12]See, for example, the efforts described in Sec. IV.

Requirements and Testing. Simple measures, with explicit and contractor-specific incentives, are also essential to strengthening requirements and testing. RAND research has identified a broad range of opportunities for improving requirements and testing to help increase the operational suitability of future weapon systems.[13] A major recommendation is to

> Expand contractual accountability for suitability-related characteristics. This requires (1) using broader R&M specification measures that more fully reflect system and subsystem maintenance demands that drive the Air Force support burden, (2) using compliance-test ground rules that do not compromise those contractual specifications through excessive exclusions of particular kinds of failure events, (3) conducting compliance tests of sufficient duration and scope to have confidence the performance measured is representative of the system at the time of the test, (4) performing more system-level compliance testing on production equipment, (5) conducting compliance tests of system characteristics that contribute to resilience to attack and mobility, and (6) including contractual mechanisms using obligations and incentives to motivate contractors to meet more stringent suitability requirements.[14]

As with warranties, the beneficial contribution of expanded contractual accountability for R&M will be influenced largely by the measures employed in contracts. For complex avionics little progress has been made in the area of developing measures that

- Provide appropriately comprehensive coverage of reliability and maintainability.
- Lend themselves to simple and explicit delineation of responsibilities.

As already noted, the fault-removal-efficiency measure fails to satisfy the later requirement.

Given continuing limitations in both the existing maintenance data and the measures that we have for characterizing R&M, we fail to find an attractive alternative to maturational development. We believe the key to such a discovery would lie in the invention of measures that can simultaneously provide the detail required by engineers and the simplicity and explicitness needed for effective contracting.

Of course, maturational development is not without its burdens. The two bottom line questions are:

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[13]Stanley and Birkler, 1986.

[14]Ibid., p. 100.

- Are the prospective benefits worth the costs?
- If so, what are the most effective ways to apply the concept?

To help answer these questions, two exploratory applications of the concept were approved during June 1981. The results of Stage 1 of these programs, launched during June 1984, are described in the next section.

IV. EXPLORATORY APPLICATIONS OF MATURATIONAL DEVELOPMENT TO THE F-16 AND F-15 RADARS

Two exploratory applications of the maturational development concept were launched during June 1984 with the objectives of learning lessons about the

1. Potential value of the concept.
2. Effective procedures for applying the concept.

Further objectives for the effort were to:

3. Better assess the R&M state of health for the subject subsystems.
4. Define the most beneficial opportunities for improving the R&M situation for these subsystems.

This section describes the technical results for the last two objectives and then draws lessons from those experiences to meet the first two objectives.

THE EXPLORATORY APPLICATIONS

Stage 1 of the exploratory application has been completed for the APG-66 radar used by the F-16 A/B and the APG-63 radar used by the F-15 C/D. The technical results fall into three categories:

- Results specific to the F-16 radar.
- Results specific to the F-15 radar.
- Results common to both radars.

The Stage 1 results are the product of a joint effort by the Air Force, RAND's Project AIR FORCE, and industry. The Air Force designated the Strike Systems Program Office (SPO), within the Aeronautical Systems Division, to manage the Stage 1 effort for both radars. RAND worked closely with the Strike SPO in formulating and guiding the Stage 1 effort, which became known as the F-15/F-16 Radar R&M Improvement Program.

RESULTS SPECIFIC TO THE F-16 RADAR

Stage 1: Assessment of R&M Situation

The Strike SPO contracted with the Westinghouse Defense and Electronic Systems Center for the four major activities constituting Stage 1 of maturational development:

- Data Collection.
- Analysis.
- Candidate Improvements.
- Formulation of an Improvement Package.

The one-year contract for approximately $6 million contained provisions under which Westinghouse contracted with General Dynamics (the F-16 weapon system prime contractor) for engineering assistance in carrying out these activities.

Data Collection. Data on the F-16's radar were collected from 150 F-16s monitored during a six-month period (June-December 1984) at Hill AFB and Hahn Air Base. These data covered 16,077 flights and the resulting radar maintenance at these bases and the depot. Contractor personnel interviewed pilots after maintenance debriefing, documenting all flight anomalies observed by the pilot, including those indicated by the BIT. Contractor personnel also documented maintenance on the flightline, in the shop, and at the depot. This effort required the fielding of a data collection team that included 32 people provided by the radar contractor (Westinghouse) and four people provided by the weapon system prime contractor (General Dynamics).

Analysis. As Fig. 4.1 shows, the radar for the F-16 A/B has six LRUs. It has tremendous versatility and can provide many functions in air-to-air and air-to-ground combat. Pilots can set switches on the control panel (see upper right), the throttle grip, and the side stick controller in over 12,000 unique configurations. Although many pilots use the same basic modes, the versatility of the radar enables them to develop individual sets of switch settings that govern antenna scan patterns, transmitter options, and display options.

This functional versatility means that pilots using the same radar have the opportunity to use it in very different ways from one flight to another. As a result, a pilot on one flight may see a fault indicated that a pilot on the next flight does not see.

For the F-16, the main R&M problems arise with the Low Power Radio Frequency (LPRF) LRU in the upper left of Fig. 4.1.[1] This unit generates microwave signals that the transmitter radiates at various

[1]The LPRF combines functions of several LRUs on the F-15 radar.

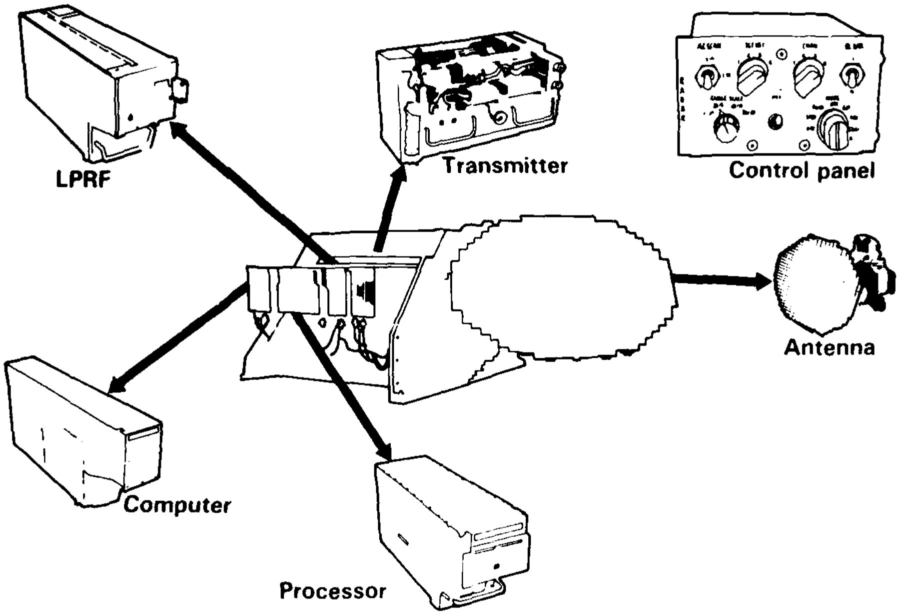

Fig. 4.1—F-16 A/B radar (APG-66)

radio frequencies. It also processes the returning microwave signals captured by the antenna. This processing is analog rather than digital and involves delicate radio frequency circuitry.

The extent and severity of the R&M problems with the LPRF were determined and validated by a four-step process that included special data collection, engineering tests, engineering analysis, and independent review.

Figure 4.2 helps show why a special data collection effort was needed. Information vital to engineering analysis would otherwise be unavailable. For example, only information such as that in the shaded rows was being entered into the standard Air Force data systems. Information in the remaining rows was unavailable even to radar maintenance technicians. It was only available to the radar contractor and only because there was a special contractor team gathering such information.

Date	BIT	Pilot Comments	Radar Op.	Radar Code	LRU Removed
June 20		Med PRF false targets in Air Mode		1	
25	032 035	MFL then screen flooded with false targets —Recycled & worked OK MFL at touchdown	OK	1	
26	057 035 032 048		Inop	2	(CND)
27		Very few returns/would not lock on to any tgts use mostly A/A. No returns in AGR.	OK	1	
27	035 032 340 048	RDR inop — no returns. Failed 5 min. after T.O. only used A/A mode	Inop	3	XMTR 0763
28		False targets	Degrd	2	(CND)
July 10		ECM pods used. —lot of false tgts & chevrons. ACM & slewable trouble locking	Degrd	1	
10		False tgts & chevrons. Radar good	OK	1	
11	055		OK	1	
13		False targets/would not hold lock O band noise bar missing	Degrd	2	(CND)
13		Numerous false targets			
24		Radar slow to lock on — had some false targets & chevrons	Degrd	1	
29		Rdr w/n lock until 17-18 miles-m/ then break, relock & worked OK	OK	1	
30		Had lots of false targets	Degrd	1	
31		Numerous false tgts throughout flight	Degrd	1	
Aug 2		Radar cursors were stuck on	OK	3	(CND)
2		Numerous false targets	Degrd	1	
6	001		OK	1	

Fig. 4.2—Performance of radar in F-16 number 0577 (June 20 through August 6, 1984)

This figure illustrates three major points:

1. *Pilots do not request maintenance for every indication of a fault in the radar.* A request for maintenance is influenced by many considerations including:
   — What does the airplane need to do on its next training flight?
   — Would the indicated fault affect the training value of the next flight?
   — What are the chances that the indicated fault was caused by microwave signals generated by something external to the aircraft?
   — What is the likelihood that technicians can duplicate the fault on the ground?
   — If the fault is duplicated, what are the chances that a replacement spare is available?
2. *Standard data systems miss many indications of degraded radar performance.* This is because information about performance degradations is regularly collected only when a pilot requests maintenance (flights that returning pilots label Code 2 or Code 3). However, a history of degraded performance may be developing even when pilots are not requesting maintenance (Code 1).
3. *The F-16's BIT often fails to detect faults, especially Type B faults.*[2] Numbers in the second column refer to specific BITs that indicate failure of the radar. Some faults, such as those causing false targets and lock-on problems, may not be caught by BITs. Other problems, such as a faulty transmitter, are only sometimes caught by BITs. In Fig. 4.2, for example, the first BIT indication of a fault in the transmitter occurred on June 25, when tests 032 and 035 failed. Although the pilot also observed indications of a problem with false targets, he did not request maintenance. BIT indications of a fault in the transmitter occurred again on the next day, and that pilot requested maintenance. However, the radar specialist Could Not Duplicate (CND) the BIT failures reported by the pilot, and the technician did not remove the radar transmitter. The first flight the following day yielded no reports of any BIT failures. But the next flight did, and the BIT failures again pointed to a faulty transmitter. Moreover, the pilot assigned a Code 3 to the maintenance request. Maintenance then removed the transmitter (XMTR) and sent it to the shop for different (and more detailed) testing and repair. The replacement transmitter

[2]However, when the F-16 radar's BIT does report the existence of a fault, the report is much more reliable than those produced by the F-15 radar's BIT.

appears to have operated as it should for the remaining five months because the BIT indicated no subsequent faults with the transmitter.

Although the transmitter problem was fixed during June, F-16 Number 0577 had other problems like those indicated during July (see Fig. 4.2) for the remaining five months of the data collection effort. Throughout the program, this airplane had more than its share of false target and target lock-on difficulties. However, these problems were rarely brought to the attention of maintenance personnel.[3] Moreover, the radar contractor would never have known about these problems if the contractor's personnel had not been present to debrief the pilots.

Part of the problem with correcting these kinds of difficulties is that they often cannot be duplicated on the ground. Maintenance technicians will therefore often assign a "CND" to the problem and wait to see what the next pilot does. The data show that the next pilot often chooses not to request maintenance, and maintenance personnel therefore do not realize that the radar is still experiencing problems.

The lack of a continuing record on how individual radars perform creates two major problems:

- Maintenance resources cannot be applied to the radars with the greatest need.
- Engineering resources cannot be applied to those radar R&M problems that cause the greatest potential degradation in performance.

Figure 4.3 summarizes data for all 150 airplanes involved in the special data collection effort. It shows that when the objective is to provide the full designed capability of the radar on a regular basis, the standard data systems portray only part of the R&M picture.

The two standard measures most frequently cited as indicators of R&M status are the fully mission capable (FMC) rate[4] and the mean time between failure (MTBF) rate.[5]

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[3]A major factor depressing pilot feedback is the frequent inability of maintenance technicians to isolate the cause of problems. For example, half of pilot requests for maintenance led to situations where the flightline maintenance technicians could not find any fault with the radar, even though subsequent analysis revealed that nearly all pilot requests were well-founded.

[4]Calculated from data collected in accordance with the Air Force's equipment status reporting procedures.

[5]Calculated from data collected in accordance with the Air Force's maintenance data collection procedures. Calculations include only failures that are determined to be relevant and confirmed by the shop.

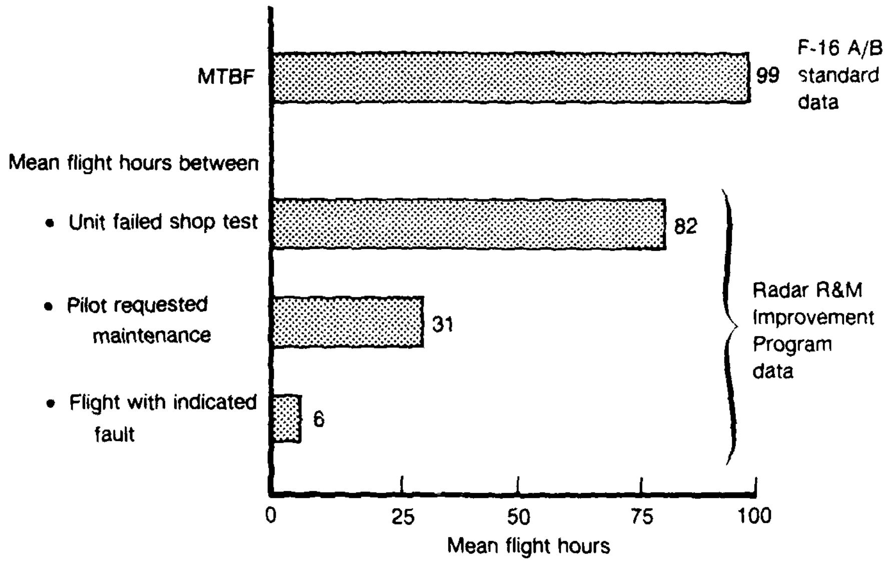

Fig. 4.3—Standard F-16 A/B data show partial R&M picture

The F-16's FMC rate is well over 80 percent, an impressive record by historical standards for this type of aircraft. Moreover, when F-16s are not FMC, equipment other than the radar mostly accounts for this status. However, the FMC rate is an incomplete measure because it drops only when pilots request flightline maintenance, and it rises again as soon as flightline maintenance is completed. For avionics, flightline maintenance usually can be completed quickly because most such actions are restricted to removing and replacing an LRU, which is then sent to the shop. Removal and replacement of an LRU or a CND action clears a Code 2 or Code 3 discrepancy but often does not correct the fault.[6]

The F-16's MTBF rate similarly causes little concern, especially since it is far larger than the MTBF for previous radars. However, this measure is also incomplete because it reflects only some situations where an LRU fails a test in the shop. Not all shop failures were counted. For example, when the flightline sent two or more LRUs from the same airplane, only one LRU failure in the shop was counted when the MTBF rate was calculated.

[6]About one half of the time such actions failed to correct a fault.

The three lower bars in Fig. 4.3 represent measures based on data specially collected by the Radar R&M Program. The first two measures are close: (1) the 99-hour MTBF, and (2) the 82 mean flight hours between units failing a shop test, as they should since MTBF is one way of looking at failures from the shop's perspective. But when radar R&M is viewed from the standpoint of flightline maintenance, there are just 31 hours between pilot requests for maintenance. And when radar R&M is viewed from the standpoint of the pilot, there are just six hours between indications of degraded performance in the cockpit.[7]

This means that if we use the avionics maintainability indicator described in Sec. III, only 7 percent of the F-16 radar's flights with one or more indicated faults led to a fault being found by the avionics shop:

$$\begin{array}{r}\text{Fault}\\ \text{Removal}\\ \text{Efficiency}\end{array} = \frac{6 \text{ MTBI}}{82 \text{ MTBF}} \times 100 = 7 \text{ percent}$$

But even the six-hour interval between flights with indicated faults fails to portray a complete picture because some faults are not indicated during every flight. Figure 4.4 shows situations when the BIT *would indicate faults during some flights but not during others.* Here, each flight with an LPRF BIT fault indicates that the radar in F-16 number 0752 failed a BIT that clearly identified a fault in the LPRF LRU. The number in each arrowhead represents the number of consecutive flights. Arrowheads in the top row represent flights in which the BIT did not indicate a fault with the LPRF. Arrowheads in the second row represent flights in which the BIT did indicate an LPRF fault.

Figure 4.4 shows an intermittent pattern: Two consecutive flights occur with faults, one without, four with, one without, and so on. This is another example of one or more Type B faults. Except for a 28-flight respite during August, this pattern persisted throughout the six-month data collection period. The 28-flight respite occurred after a pilot requested maintenance and radar technicians replaced the LPRF. However, even during these 28 flights, the pilot observed faults that

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[7]A flight with an indicated fault is any flight in which the pilot reported one or more fault indications to a contractor data collector during the special interview following the maintenance debrief. Fault indications included situations when the radar failed a BIT as well as when the pilot believed the radar operation was not fulfilling its designed capability. Some of the pilot-reported observations of difficulty may have been occasioned by increased expectations induced by the presence of the contractor's data collectors. The resulting effect on the six hours must be small, however, because 80 percent of the flights with indications had one or more faults detected by the BIT.

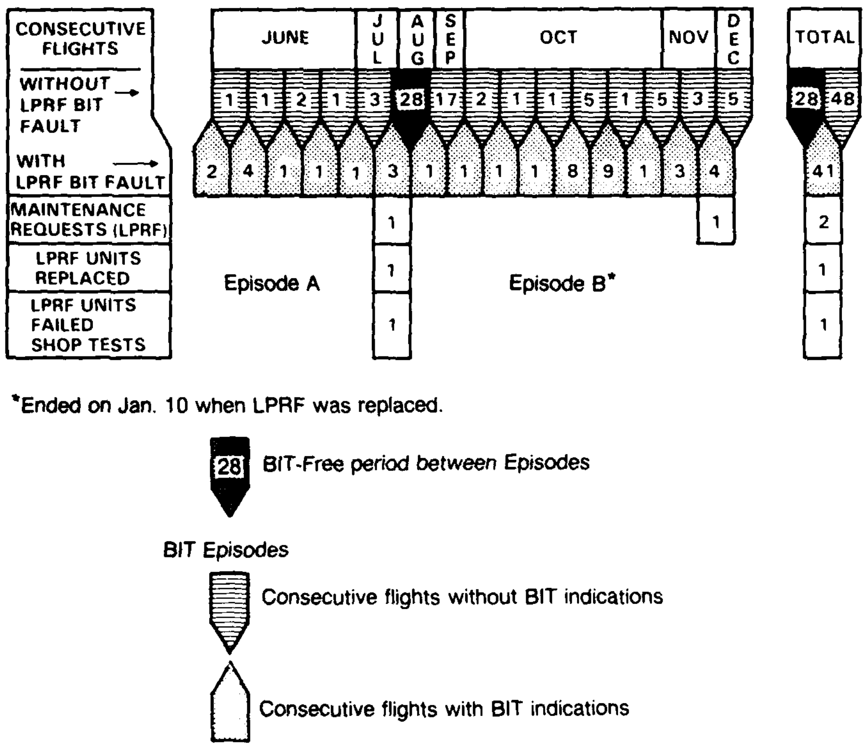

Fig. 4.4—LPRF history: F-16 number 0752 (June through December 1984)

the BIT eventually picked up, so it is reasonable to assume that one or more faults occurred in the replacement LPRF. Yet throughout the six months there were only two requests for maintenance and only one LRU removed.[8]

It is also reasonable to believe that during the other 89 flights before and after that 28-flight period one or more faults occurred in the LPRF that could inhibit the radar from delivering its full designed capability. Thus, although only 41 flights yielded BIT indications of faults, twice that number of flights were apparently flown with one or more faults present in the LPRF.

Finally, Fig. 4.5 summarizes the LPRF BIT failures for the 10th Tactical Fighter Squadron (representative of the six squadrons

[8]Moreover, Westinghouse tracked this airplane for an extra month, until the Air Force—at Westinghouse's suggestion—removed and repaired this LRU.

monitored) for an entire six-month period. The left column identifies the specific aircraft. Unshaded portions of the bars represent series of flights during which the BIT indicated the LPRF had functioned properly. Shaded portions represent series of flights during which the BIT indicated the LPRF had failed to function properly.

Fortunately, not all airplanes look like 0752. For example, the BIT in number 0556 found no faults in the LPRF for the entire four-month period that it participated in the data collection program. Altogether, 12 airplanes in this squadron had no faults in their LPRFs as indicated by their BITs. However, ten airplanes encountered protracted periods spanning several months during which they had faults in their LPRFs. (The fact that so many aircraft are afflicted with LPRF faults had not been documented before the data collection effort.)

Candidate Improvements. Figure 4.6 shows the current LPRF unit, which is the primary source of radar R&M problems for the F-16

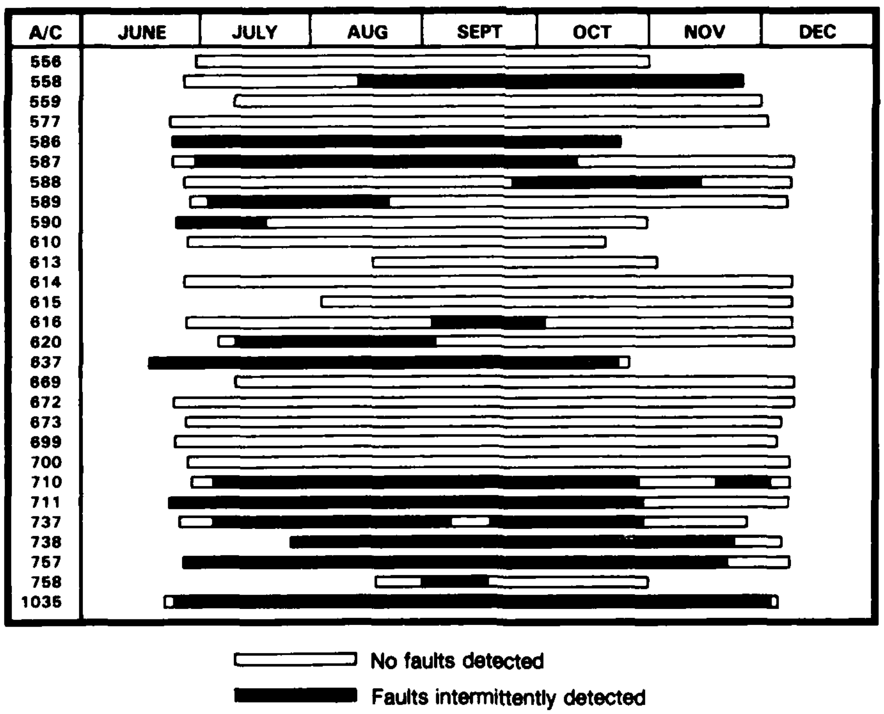

Fig. 4.5—LPRF BIT failure episodes: 10th TFS
(June through December 1984)

radar. Although critical to the F-16's wartime mission, this LPRF has never adequately "matured."

As with the radar and other modern avionics on the F-16, this unit rarely experiences a failure severe enough to render it totally incapable of supporting the airplane's missions. Its most common failure modes have two characteristics:

- They degrade the available level of performance by reducing detection ranges, introducing target tracking problems, or creating false targets.
- They manifest themselves mostly when the radar is exposed to thermal and dynamic stresses from the airplane's operational environment. Thus the BIT will frequently catch a fault during flight but later fail to duplicate it when the airplane is on the ground.

The dominant causes of such performance degradations are a material incompatibility problem in the receiver module and a packaging of the LRU that complicates reassembly of the unit after maintenance. The material's problem is worsening with age because a chemical process is causing deterioration of delicate circuits. The reassembly problem is caused by a packaging design that requires extensive disassembly to gain access to faulty components. The reassembly process requires the technician to connect and align several delicate rf fittings that are hard to access. (The more easily accessed fittings are visible in Fig. 4.6.)

The Radar R&M Program identified three causes of problems with the LPRF:

1. Connections between modules. Delicate radio frequency connections between modules have stringent alignment and torque requirements. Technicians must undo many of these connections to get at modules and circuit cards inside the LPRF. Imprecise refastening can let the dynamic flight environment disrupt signals and thereby lead to false targets and trigger BIT failures; clearance limitations in the present design make precise refastening very difficult to achieve.
2. Components within modules. Several components within modules fail mostly when subjected to thermal and flight

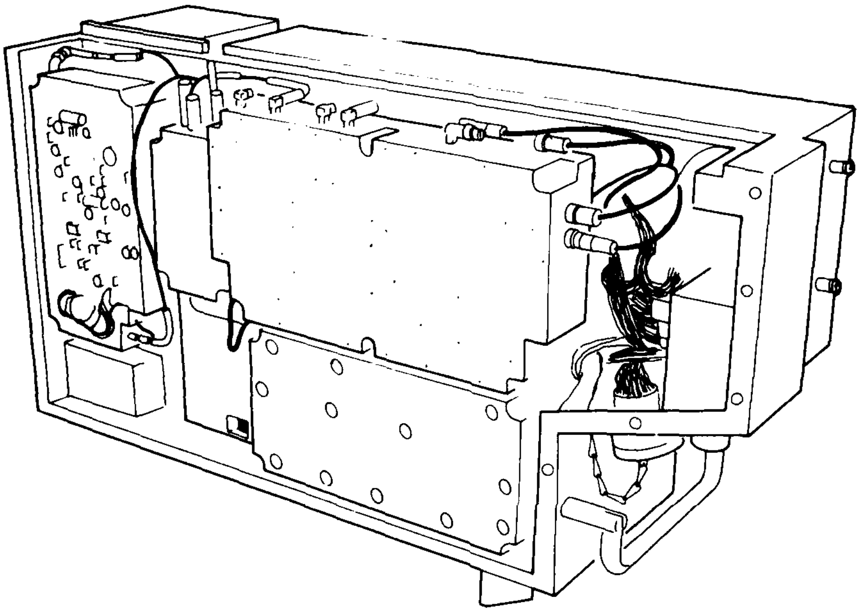

Fig. 4.6—Current LPRF for the F-16

dynamic stresses. Thus the BIT often finds faults in flight that neither it nor the shop can find on the ground.[9]

3. Connections between components within modules. Deterioration of connections within the receiver module is occurring throughout the module where indium solder joins gold conductor ribbons. The indium solder absorbs molecules in the connector ribbon, and as these molecules migrate they leave voids in the conductor ribbon that coalesce to form minute flaws. When exposed to the cyclic stresses created by the time-varying thermal and dynamic environment, these flaws enlarge much like a fatigue crack would in an airframe structure. Eventually, the connector ribbon breaks away from the solder and causes an open circuit that the shop's test equipment can readily detect. Long before separation, however, the quality of the radio

[9]Both shops and depots test the equipment at normal room temperatures and in a dynamically benign environment rather than under simulated flight environment conditions.

> frequency circuitry begins to degrade, and such degradation can manifest itself in the form of BIT-detected faults, false targets, tracking problems, and the like.

These problems with the LPRF are worsening with age, as evidenced by a 60 percent increase in monthly receiver repairs from 1984 to 1985.

Before the special data collection and analysis effort, problems with the LPRF were masked by the confluence of several factors. For one thing, a radar with a 99-hour MTBF does not draw much attention,[10] especially when it was not known that there were only six hours between flights with indicated faults (and 80 percent of these indications were by the BIT). Moreover, false targets, target tracking problems, and the like can often result from factors external to the aircraft. In addition, the extent of environment-sensitive failure modes was unknown. Before the special data collection, there were no records that could pinpoint indicated fault trends to system-specific problems. Finally, many faults detected by the BIT were thought to result from a grounding problem that could be corrected by a new shim that would provide a tighter electrical path for grounding the radar equipment to the airframe.[11]

In part, problems with the LPRF resulted from squeezing a capable and versatile radar into a very small volume with a tight weight limitation and a limited amount of environmental cooling. Advances in technology will now permit a more maintainable LPRF that should be less prone to the kinds of connection and component problems that plague the current design.

To explore this idea, the Radar R&M Program commissioned Westinghouse to develop a preliminary design for a new LPRF that would draw on technologies that Westinghouse was already incorporating in its newer radars (see Fig. 4.7). This new design resolves the receiver problem and enables more circuitry to be packaged into a smaller volume. Such packaging is also more modular and facilitates disassembly. With connections on the back of each module, shop technicians would no longer have to disrupt as much of the delicate radio frequency circuitry to remove a module such as a redesigned receiver.

R&M Improvement Package. Redesign of the LPRF would serve as the cornerstone in implementing maturational development improvements for the F-16's radar. A complete package would include

[10]The F-4's radar has less than a 9-hour MTBF.

[11]Special tests showed that the new shim would not correct problems the BIT was attributing to the LPRF: Of 20 aircraft that received new shims, 19 were found to have faulty LPRF units that caused the BIT fault indications.

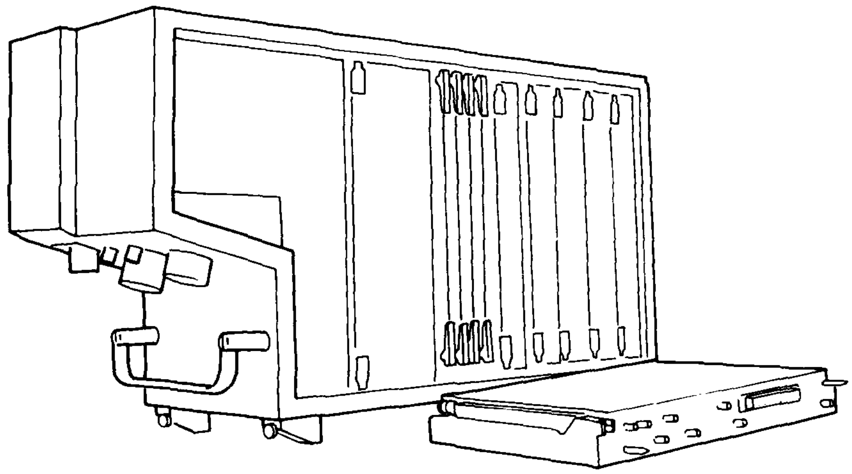

Fig. 4.7—New LPRF design for the APG-66 radar in the F-16 A/B

the items listed in Table 4.1 and would fall into three priority classifications based on subjective assessments of their potential benefits.[12] Priority 2 improvements for the F-16 radar consist of

1. Redesigning and re-routing the *antenna cable* to allow replacement at the avionics shop and thus avoid having to send the entire antenna to the depot for cable replacement.
2. Using recently developed technologies to improve the maintainability of the *radio frequency test station*, currently the most difficult station to maintain in the avionics shop.
3. Instituting *environmental testing* at the depot to improve repair of the current LPRF and other bad-actor equipment.[13]

Priority 3 improvements for the F-16 consist of

1. Changing *Technical Orders* to make them more consistent, compact, accurate, and useful for maintenance personnel.

[12]In spite of these classifications, we recommend that the Air Force pursue all the identified improvements.

[13]During the data collection and analysis program, 30 suspected bad-actor LRUs were sent to the contractor. By just applying cold soak to these LRUs and then testing them, the contractors were able to isolate the faulty SRUs in two-thirds (20) of the LRUs. By adding a vibration environment to the test they may have been able to isolate the remaining LRUs' faults.

2. Correcting deficiencies in *shop software* that allow certain faults to escape detection.

(The "generic improvements" listed in Table 4.1 are described at the end of this section.)

Such a total improvement package could triple the mean time between indicated faults (from six hours to 19 hours) and also reduce the maintenance workload by 35 percent. In total, this development package (excluding Priority 3 items) would cost $250 million.[14] Although some of this cost could be offset by the decreased need for maintenance, the main benefit would be in increased availability of radars that are prepared to dependably deliver the performance they were designed for.

Table 4.1

A MATURATIONAL DEVELOPMENT IMPLEMENTATION PACKAGE FOR THE F-16'S RADAR

	Priority 1	Priority 2	Priority 3
F-16 Specific	LPRF	Antenna cable Radio frequency test station Depot environmental testing for LPRF	Technical Orders Shop software
Generic	Tracking equipment by serial number Test translation dictionaries	Direct entry testing Loop testing	Material deficiency reporting Technical Orders feedback Interactive pilot debrief

[14]Quantitative estimates for costs and benefits were derived from the technical data packages that Westinghouse delivered to the Strike SPO. We reviewed the data packages as did a Technical Coordinating Committee that included R&M engineers from the Air Force Acquisition Logistics Center, an independent contractor (Support Systems Associates, Inc.), and personnel from the strike SPO. The independent contractor and the RAND personnel monitored both the data collection and the engineering analysis efforts.

Stage 2: Implementation of Improvements

At present we can report the current status of three recommended R&M improvements for the F-16 A/B radar:

- The design effort on a new LPRF (Priority 1) is scheduled to start in 1989.
- The new design for an antenna cable (Priority 2) has completed development.
- Changes to TOs (Priority 3) have been submitted.

RESULTS SPECIFIC TO THE F-15 RADAR

Stage 1: Assessment of R&M Situation

For this radar, the Strike SPO contracted with the Hughes Aircraft Company for the four major activities constituting Stage 1 of maturational development. The one-year contract for approximately $6 million contained provisions under which Hughes contracted with McDonnell Douglas (the F-15 weapon system prime contractor) for engineering assistance.

Data Collection. Data on the F-15's radar were collected from 150 F-15s monitored during a six-month period (June-December 1984) at Langley AFB and Bitburg Air Base. These data covered 16,702 flights and the resulting radar maintenance at these bases. As with the F-16's radar, contractor personnel interviewed pilots after every flight and then documented maintenance on the flightline, in the shop, and at the depot. This effort required the fielding of a data collection team that included 32 people provided by the radar contractor (Hughes) and four people provided by the weapon system prime contractor (McDonnell Aircraft).

Analysis. The radar for the F-15 C/D is more powerful, has a larger antenna, and is heavier and more complicated than the F-16 radar. It also has more capability even though its technology precedes the F-16's radar by about four years. As Fig. 4.8 shows, the F-15 radar has nine LRUs in addition to the throttle, stick, and connectors. This number of LRUs creates problems because the BIT on this radar, unlike that on the F-16, is not dependable at identifying the LRU that the technician should remove.

For the F-15 radar, the main R&M problems arise with the BIT itself. The F-15's BIT aims at detecting faults in the radar and at isolating the causes to a particular LRU. Neither it nor other BITs, however, isolate faults in cables and connectors. The BIT operates during

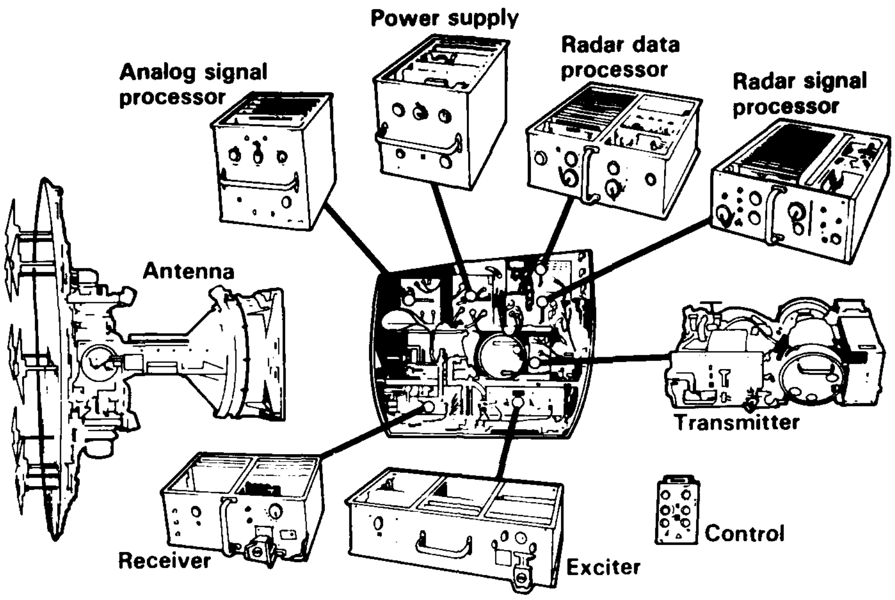

Fig. 4.8—F-15 C/D radar (APG-63)

flight in a mode called "continuous monitor" in which it provides short, periodic tests. In addition, the operator can use it on the ground or in flight to initiate comprehensive, three-minute tests.

The extent and severity of the R&M problems with the BIT were determined and validated by a three-step process that included special data collection, engineering analysis, and independent review. Figure 4.9 summarizes data for all 150 airplanes involved in the special data collection effort.

The F-15's FMC rate is well over 70 percent and thus might suggest no serious R&M problems. Moreover, Fig. 4.9 shows the F-15's radar MTBF rate is 23 hours, much lower than the 99 for the F-16's radar but also much higher than the single-digit MTBF for the F-4's radar. This difference should not be too surprising because the F-15's radar is more complex and represents an older technology than the F-16's radar.

The three lower bars of Fig. 4.9 represent measures based on the Radar R&M program data. Again, the first two values are close: (1)

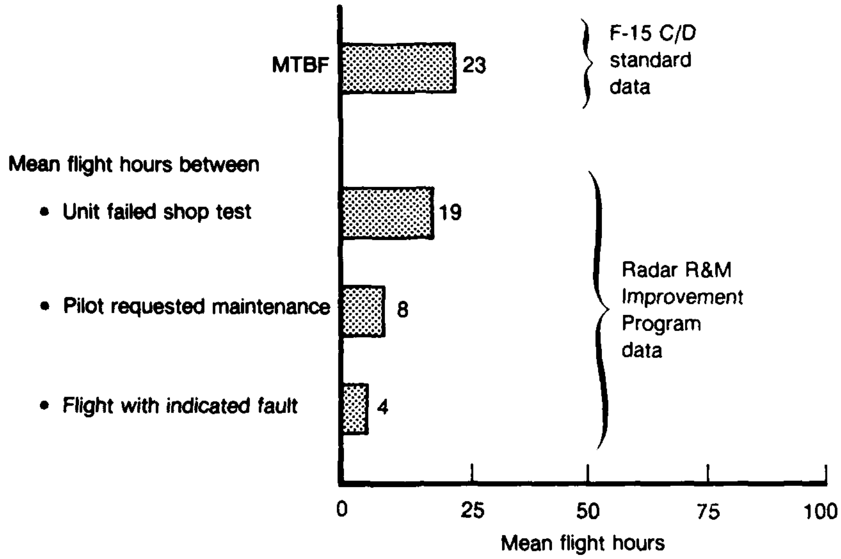

Fig. 4.9—Standard F-15 C/D data show partial R&M picture

the 23-hour MTBF, and (2) the 19 mean flight hours between units failing a shop test, as MTBF is one way of looking at failures from the shop's perspective.

But when radar R&M is viewed from the standpoint of flightline maintenance and its problems of dealing with the faulty BIT, there are just eight hours between pilots' requests for maintenance. And when radar R&M is viewed from the standpoint of the pilots and their problems with both the radar and the faulty BIT, there are just four hours between indications in the cockpit of degraded performance.

This means that if we use the avionics maintainability indicator described in Sec. III, only 21 percent of the F-15 radar's flights with one or more indicated faults led to a fault's being found by the avionics shop:

$$\begin{array}{c}\text{Fault}\\ \text{Removal}\\ \text{Efficiency}\end{array} = \frac{4\ \text{MTBI}}{19\ \text{MTBF}} \times 100 = 21\ \text{percent}$$

Indeed, 28 percent of the time that a pilot saw a problem with the radar, the BIT failed to indicate a fault. According to Hughes's engineering analysis of their collected data, up to 35 percent of the time that the BIT indicates a failure, the indication is wrong. And when the BIT detects a real failure, up to 35 percent of the time the BIT isolates the fault to the wrong LRU, which causes maintenance technicians to look in the wrong place. The low dependability of the BIT means that problems can linger in the aircraft for long periods of time before they are finally located and solved.

A faulty BIT means several things. Sometimes the BIT indicates a fault when there is none. At other times the BIT does not indicate an existing fault. All of this leads pilots and maintenance personnel to distrust the BIT. This distrust has, among other things, led maintenance personnel to swap LRUs between airplanes to isolate faulty units. But this kind of inefficiency, necessitated by the low dependability of the BIT, greatly increases the maintenance workload.[15]

Figure 4.10 documents this inefficiency by showing that maintenance personnel have to remove almost twice as many LRUs as actually have problems. Each of the clear bars represents the number of occurrences for the events defined in the left margin. If the maintenance process perfectly followed the underlying maintenance concept, all of the clear bars would have the same length. That is, for each maintenance request, one problem would be found, one LRU would be removed, and one LRU would be sent to the shop. The shaded bars explain deviations from this ideal. For example, the "Maintenance Requested" bar greatly exceeds the "Problem(s) Found" bar. The reason lies in the shaded "Can Not Duplicate" bar. These were events when flightline maintenance personnel could not duplicate symptoms for the problems for which the pilot had requested maintenance.

The next major deviation occurs between the "Problem(s) Found" bar and the "LRU Removed" bar. Far more LRUs are being removed than there are problems. In fact, the number of extra LRU removals is even greater than the difference in the clear bars because some of the problems are dealt with by fixing a connection problem that lies between LRUs—no LRU is removed. There were nearly two LRUs removed for every problem that required an LRU removal. Many of these extra removals were LRUs that were moved between aircraft to facilitate fault isolation. Some, however, were sent to the shop (this is the difference between the last two shaded bars). In fact, the shop received about one-fourth more LRUs than there were problems.

In sum, BIT deficiencies increase the maintenance burden by nearly doubling flightline removals and by increasing shop arrivals by one-fourth.

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[15]It also wears the connectors and wires that join LRUs together. Connector and wiring problems are especially hard to isolate.

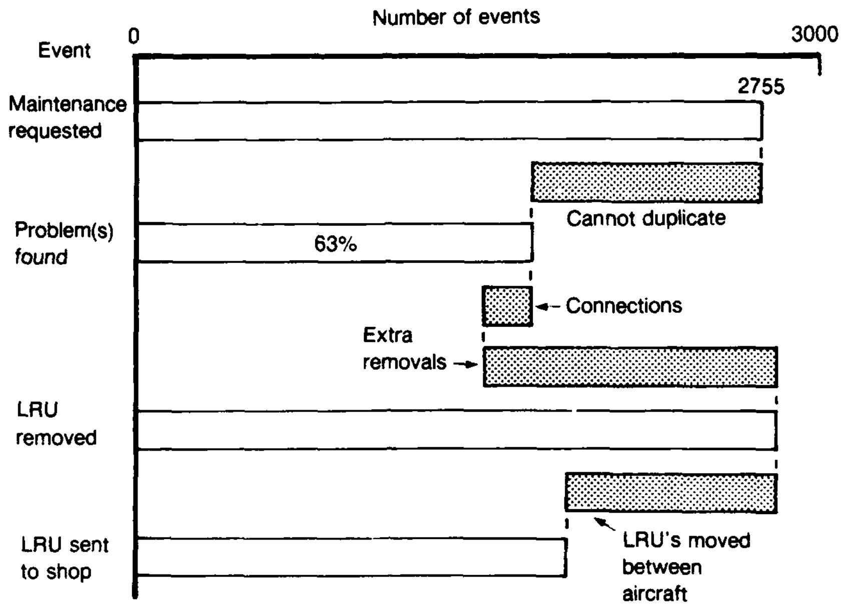

Fig. 4.10—Flightline maintenance events: F-15 radar (June through December 1984)

Candidate Improvements. To deal with the F-15's BIT problems, the Radar R&M Program identified three needed improvements:

1. Improvements to the BIT software. Although new tactical software is developed and tested each year, the BIT has not been retested. During the Radar R&M Program, Hughes engineers found ten situations in which the BIT, because of the way that it is interleaved with the tactical software, falsely indicates the presence of faults.
2. Additions to the BIT hardware. During the data collection effort, Warner Robins ALC was working on ground support equipment that could augment the BIT function. Since this equipment necessarily requires up to two or three hours for use, it was not designed to support the quick turnarounds required in wartime. It could, however, be available within about two years.
3. Improvements to the BIT hardware. Adding memory and test points to the BIT hardware would provide more of the capabilities that are being incorporated in the ground support

equipment and would allow quick turnarounds without more ground support equipment.

Since the F-15 radar first entered operational service in 1975, it is reasonable to enquire why the BIT deficiencies had not been resolved much sooner. A major factor is that the radar R&M program provided the radar contractor the first opportunity to make an in-depth, first-hand engineering examination of what was happening in the field. Although the radar contractor had had technical representatives assigned to various bases over the years, these representatives could not begin to collect the kinds of data needed to define the specific engineering deficiencies with the current BIT.

Improvement Package. Improvements to the BIT's software and hardware would serve as the cornerstone in implementing maturational development improvements for the F-15's radar. A complete package of these improvements would include the items listed in Table 4.2. The improvements fall into three priority classifications based on subjective assessments of their potential benefits.[16] Priority 2 improvements for the F-15 consist of

1. Undertaking *LRU fixes* to improve the reliability for the radar's exciter, transmitter, receiver, antenna, analog processor, programmable signal processor, and power supply.
2. Adding dynamic test and fault-isolation capabilities for the *Antenna A Test Station* in the avionics shop.
3. Instituting environmental testing and adding a complete radar test bench to the *depot equipment*.[17]
4. Undertaking research, evaluation, and selection of a replacement for *coolanol*, which is prone to contamination.

Priority 3 improvements for the F-15 consist of specific changes proposed for

1. Changing *Technical Orders* to make them more consistent, compact, accurate, and useful for maintenance personnel.
2. Correcting deficiencies in *shop software* that allow certain faults to escape detection.
3. Identifying reasons why problems with SRU connections apparently disappear when maintenance personnel *reseat* the SRU in the LRU.

[16]In spite of these classifications, we recommend that the Air Force pursue all the identified improvements.

[17]The test bench allows technicians to test any radar LRU as part of the overall radar subsystem.

Such a total improvement package could triple the MTBI faults (from four hours to 13 hours) and reduce the maintenance workload by 50 percent. In total, this development package (excluding Priority 3 items) would cost $200 million.[18] Although some of this cost could be offset by the decreased need for maintenance, the main benefit would be in the increased availability of radars that are prepared to dependably deliver the complete performance they were designed for.

Stage 2: Implementation of Improvements

At present, we can report the current status of five recommended R&M improvements for the F-15 C/D Radar:

- Development of the BIT Software (Priority 1) is underway and flight testing of the new software was scheduled for September 1987.
- LRU reliability fixes and depot equipment (both Priority 2) are underway.
- The study of a coolant replacement (Priority 2) is in progress.
- Changes to TOs (Priority 3) have been submitted.
- Study of the reseat problems (Priority 3) is underway.

Table 4.2

A MATURATIONAL DEVELOPMENT IMPLEMENTATION PACKAGE FOR THE F-15'S RADAR

	Priority 1	Priority 2	Priority 3
F-15 Specific	BIT software and hardware	LRU fixes Antenna A Test Station Depot equipment Replacement of coolanol	Technical Orders Shop software Reseat problems
Generic	Tracking equipment by serial number Test translation dictionaries	Direct entry testing Loop testing	Material deficiency reporting Technical Orders feedback Interactive pilot debrief

[18]Quantitative estimates for costs and benefits were derived from the technical data packages that Hughes delivered to the Strike SPO. The same Technical Coordinating Committee that reviewed the Westinghouse data packages reviewed these as well.

RESULTS COMMON TO BOTH RADARS

Stage 1: Assessment of R&M Situation

Although these exploratory applications of Stage 1 of maturational development concentrated on radars for the F-16 and F-15, the common results are potentially applicable to other types of similarly sophisticated airborne electronics, such as weapon delivery and electronic warfare equipment, and to other combat aircraft, such as attack aircraft and bombers.

The Stage 1 results for both radars showed faults escaping detection in the cockpit, on the flightline, in the avionics shop, and at the depot. Because testing was found to be far from infallible at every level of maintenance, and because faults that were correctly detected were sometimes not correctly fixed, many faulty units circulated through the system and back into the airplanes. Such units left a history of degraded performance that the standard data collection system did not detect.

This circulation of faulty units through the system created three major problems. First, airplanes with faulty units could not dependably deliver their full range of designed capabilities. This situation introduces an intolerable uncertainty into the combat arena. Second, pilots often could not recognize these faults because of the multicapability nature of their avionics equipment. Third, faulty units sooner or later displayed degraded performance, and maintenance technicians again had to deal with them. When faulty units make multiple passes through maintenance, the maintenance workload is artificially increased—an all too frequent occurrence with the F-15 and F-16 radars.

Taken in conjunction with maturing of the F-16 and F-15 radars, seven generic changes applicable to the support process for both radars can greatly improve the R&M situation. These improvements fall into three priority classifications based on subjective assessments of their potential benefits:[19]

Priority 1. Tracking equipment by serial number, and test translation dictionaries.

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[19]In spite of these classifications, we recommend that the Air Force pursue all the identified improvements.

Priority 2. Direct entry into test sequences, and loop testing.

Priority 3. Material deficiency reporting, TO feedback, and interactive pilot debriefing.

Priority 1 improvements aim at more rapid identification of faulty units.

Tracking Equipment by Serial Number. Table 4.3 identifies by serial number the specific F-15 radar LRUs that made multiple visits to the shop during the six-month special data collection period. Technicians use the term "bad actors" for repeatedly faulty LRUs that the shop cannot correct. Programmable Signal Processor #1059 made a dozen visits to the shop in six months when one would expect to see it in the shop no more than once. Perhaps the symptoms of the fault(s) with this bad actor were stimulated only in the flight environment, which the shop could not duplicate, or perhaps the shop's testing procedures failed to detect the problem because of a void in the test logic.

Effective tracking of equipment by serial number must begin with a full debriefing of the pilot during which all indications of faults are reported to maintenance. It then involves record keeping by maintenance personnel on the flightline, in the shop, and at the depot concerning the status of equipment taken from the airplane, tested, and repaired.

Table 4.3

F-15 RADAR LRUs WITH MULTIPLE VISITS TO THE SHOP[a]

Unit Type and Serial Number	Visits per Unit
Programmable signal processor #1059	12
Transmitter #0067	10
Programmable signal processor #1015	9
Transmitter #0525	8
Receiver #0471	8
Analog signal processor #0561	8
Programmable signal processor #1057	8
Antenna #0855	7
Seven various units	6
Seventeen various units	5

[a]Data collected at Bitburg Air Base, June to December 1984.

This kind of tracking of equipment by serial number has long been a contentious subject. The logistics community has not yet universally accepted this need. As some logisticians see it, the development community should solve the problem by improved designs for LRUs; maintenance personnel should not have to keep detailed historical records because their primary job is to be prepared to fix airplanes quickly. Although placing greater burdens on the developers may help upcoming systems, it will not help currently fielded weapon systems. For these systems, tracking equipment by serial number can help identify specific bad actors that waste maintenance resources and undermine fighter effectiveness.

We believe that this kind of improved information is essential to improved training of avionics maintenance personnel. On a few occasions we have had the opportunity to compare the performances of contractor maintenance personnel with those of less well-trained and less experienced Air Force maintenance personnel; we have seen no difference in the effectiveness of Air Force personnel performances as measured in terms of mean flight time between LRU removals on the flightline, mean flight time between LRU failures verified by the shop, and percent of LRUs that bench check serviceable (BCS) in the shop (see Table 4.4).[20] These two groups have the same record in dealing with faulty LRUs largely because they must deal with the same kinds of *limited* information.

Test Translation Dictionaries. Faulty units can often slip undetected through several layers of maintenance because testing varies from level to level. Tests in the airplane are different from tests in the shop, and tests in the shop are often different from tests in the depot. LRUs at the depot receive the same tests as those in the shop, but SRUs at the depot undergo more detailed testing. Unfortunately, tests at these different levels speak "different languages." Thus technicians at one level often cannot benefit from the testing done at another level.

"Translation dictionaries" could enable technicians at one level to translate test results from some other level into terms they can find useful. Technicians must use information from the previous level to confirm that they are correcting failures discovered at the previous level. If test results at a more detailed level do not verify results from the preceding level, the unit may be a bad actor and require special surveillance by pilots and flightline maintenance personnel. And if the

[20]A BCS occurs when an LRU received by the shop passes all shop tests without maintenance being performed. Typically, 35 percent of complex avionics LRUs bench check serviceable in the shop.

Table 4.4

EFFECTS OF TRAINING AND EXPERIENCE ON MAINTENANCE PERFORMANCE[a]

Measures of Maintenance Performance	Contractor Maintenance Personnel	Air Force Maintenance Personnel
Mean flight time between avionics		
LRU removals on the flightline	2.1 hrs	2.0 hrs
LRU failures verified by the shop	3.0 hrs	2.9 hrs
Percent of avionics LRUs that bench checked serviceable	30.2	27.5

[a]Data was collected as part of the F-111D MK II Fault Isolation Verification Program. Data on General Dynamics maintenance personnel cover 179.4 flight hours between December 12, 1973, and March 21, 1974; data on Air Force maintenance personnel cover 14,667 flight hours between January 1, 1973, and December 31, 1973. This information was extracted from the personnel files of H. L. Shulman, who was instrumental in initiating and directing the program.

unit's anomalous behavior persists, it needs to be sent to the depot for special testing and analysis.

During the radar R&M program, radar contractors were able to identify and fix bad actors because their engineers could track equipment by serial number and perform needed translations of test results. Moreover, there were two very important and interesting discoveries:

- In the case of the F-16 radar, the LPRF accounted for most of the LRUs entering the shop. But half of these LRUs would bench check serviceable. Tracking specific units by serial number indicated that most of these units were indeed faulty.
- In the case of the F-15 radar, about 35 percent of the LRUs entering the shop would bench check serviceable. Moreover, for an additional 20 percent that received maintenance actions, those actions were unrelated to real inflight faults. Less than half of the LRUs entering the shop had maintenance performed that was relevant to inflight faults.

Priority 2 improvements aim at increasing shop and depot capability to find faulty SRUs within LRUs even when the SRUs suffer from Type B faults.

Direct Entry into Test Sequences. Most tests of complex avionics at the shop and depot involve a lengthy sequence that always runs in the same order and often requires long periods of time, even hours, to complete. Technicians generally cannot directly enter the test sequence at a particular point. This inhibits their ability to find faults that are sensitive to time-varying thermal conditions, especially those faults that can be detected only during the early stages of testing when the equipment has not yet reached thermal equilibrium.

Contractor engineers were able to devise ways to directly enter some test sequences during the radar R&M program. In many cases this proved to be an effective maintenance aid.

Loop Testing. Although most tests of complex avionics at the shop and depot are more detailed and thorough than those in the airplane, one exception is tests run by the continuous monitor BIT. Depending on the mode of radar operation, the repetition frequency for BIT tests may be high or low. When high, the BIT has the advantage of repeated loop testing that can find faults with intermittent symptoms. If technicians in the shop and depot could achieve comparable test repetitions, they could better identify and correct Type B faults.

During the radar R&M program, the radar contractors found that their engineers could use their special knowledge of test equipment to apply the direct entry technique and to institute loop testing to find intermittent faults that had eluded routine procedures.

Next we consider *Priority 3* changes, which aim at improving the ability of maintenance technicians at all levels (flightline, shop, and depot) to identify deficiencies in the design of airborne equipment and ground-based support equipment, in documentation for maintenance, and in the debriefing of pilots.

Material Deficiency Reporting. The Air Force has a formal process whereby maintenance technicians can report deficiencies in the design of airborne equipment and ground-based support equipment.[21] Each radar contractor found that maintenance technicians often do not use the process. Technicians commonly complained that

- A great deal of time usually elapses between submitting a report and receiving a response
- The quality of the response is usually quite low.

[21]In this context, equipment includes not only the hardware but also the associated software.

Moreover, Air Force personnel responsible for responding to technicians' reports acknowledged that they did not have adequate resources to review reports and initiate corrective actions. The entire process needs to be evaluated and appropriate resources applied to it.

A related measure that could help the process is tracking of individual items of equipment following maintenance. (Each item has a distinct serial number.) Such a procedure would provide information that technicians could use to better document support deficiencies.

Technical Orders Feedback. The Air Force has a formal process whereby maintenance technicians can report deficiencies in the TOs that prescribe how maintenance should be done. The radar contractors reported that this process suffers from the same afflictions as the material deficiency reporting process. This is an especially serious situation because TOs are inevitably immature when initially fielded and consequently need extensive field participation for their improvement.

During the radar R&M program, maintenance technicians were seldom observed referring to technical manuals except when dealing with the most difficult faults, such as wiring problems. Again, the entire process needs to be evaluated and appropriate resources applied to it.

Interactive Pilot Debriefing. Both radar contractors found that debriefing of pilots is commonly handled by maintenance personnel who lack specialized knowledge about the radar and who often must debrief multiple sorties by several pilots at a given time. Because of the shortcomings of these debriefings, pilots fail to provide information necessary to identify faults and fault codes, and maintenance personnel often ignore the radar malfunction codes produced at debriefing.

In particular, debriefers unfamiliar with the radar experience great problems using the Fault Code Manual. During the radar R&M program, debriefing personnel correctly assigned the proper fault code only 35 percent of the time.

Because of these problems, we recommend that the Air Force explore the possibility of a computer-aided automated system that would provide a hierarchical menu of questions concerning malfunctions reported by pilots. Such an interactive system may provide maintenance technicians better information for trouble-shooting the radar system.

Stage 2: Implementation of Improvements

At present we can report the current status of three recommended R&M improvements common to both radars:

- A prototype of a system for tracking equipment by serial number (Priority 1) is undergoing development and testing at Bitburg Air Base (see Sec. VI for further details).
- As an interim measure, the Air Force has reduced the scope of the Material Deficiency Reporting process (Priority 3) to reduce the quantity of MDRs that must be handled.
- A prototype of an interactive pilot feedback debrief (Priority 3) is undergoing evaluation at the Air Force Logistics Management Center.

LESSONS LEARNED

From these exploratory applications we learned:

- The value of the concept of maturational development.
- Effective procedures for applying the concept.

Value of the Concept

Because Stage 2 is still in progress, most lessons about the potential value of the concept must be inferred from the Stage 1 results. What was learned during Stage 1? What benefits and costs would be expected from implementing the Stage 1 recommendations?

Although data pointing to problems with the F-16 LPRF unit and the F-15 BIT existed long before the 1984 data collection, the pre-1984 data lacked depth, context, and credibility. Data were shallow because the prevalence and effect of the problems were only partially documented and the relative contributions of the underlying causes were unknown. The context of data was incomplete and ambiguous because not all R&M deficiencies and their interrelations were fully assessed; consequently, other problems appeared far more dominant. Data lacked credibility because the radar development contractors' engineers were mostly detached from the various pre-1984 assessments. Although no new major problem areas were discovered, root causes of problems were identified and sorted out in terms of their effect. The result of this process is a prioritized package of improvements.

Table 4.5 shows estimates for the main costs and benefits of full incorporation of the Priority 1 and Priority 2 improvements listed in Tables 4.1 and 4.2. *The main benefit lies in more rapid restoration of combat-essential equipment to a state of full designed capability.*

Table 4.5

BENEFITS AND COSTS OF IMPLEMENTING RECOMMENDED PRIORITY 1 AND PRIORITY 2 IMPROVEMENTS

Radar	Mean Time Between Confirmed Failure[a] (hours)	Fault Removal Efficiency[b] (%)	Additional Cost (million 1984 $)
APG 63 on the F-15 C/D			
Observed during 1984	19	21	
Projected with improvements	25	50	200
APG 66 on the F-16 A/B			
Observed during 1984	82	7	
Projected with improvements	100	55	250

SOURCE: Compiled from data packages that Hughes and Westinghouse provided to the Strike SPO.

[a]MTBF is based on shop confirmation of failure.

[b]A fault removal efficiency of 21 percent means that 21 percent of the flights with a radar fault indicated ended up with the support process removing one or more faults.

Effective Procedures for Applying the Concept

Given that a subsystem is selected for maturational development, what lessons can we draw from the two radar applications? What aspects of the exploratory application were especially effective? What aspects might be strengthened in future applications?

Especially Effective Procedures. The Air Force's execution of the exploratory applications of the concept proved to be especially effective in seven respects:

- Stage 1 funding with resources that were dedicated to assessing the radar R&M situation and were kept independent from ongoing radar development or support efforts.
- Stage 1 management by an independent SPO (the Strike SPO).
- Strike SPO utilization of an integrating contractor[22] to help oversee and evaluate the equipment contractor efforts.

[22]Support Systems Associates, Inc.

- Engineering assistance supplied to the Strike SPO by the Air Force Acquisition Logistics Center.
- Direct contracting with the subsystem contractors.
- Subsystem subcontractors contracting with the weapon system prime contractors for engineering support.
- Contractors collecting and analyzing data on their own equipment.

Opportunities to strengthen future applications. Two aspects of the exploratory applications leave opportunities for improvement by future applications of the concept:

- Assure an earlier start for Stage 1 by making a commitment to Stage 1 well before the IOC date both for
  - Funds,
  - Program management direction.
- Strive for more timely and more effective implementation of the Stage 2 improvements by
  - Assigning lead responsibility (and staff) to a single organization (as was done for Stage 1),
  - Reserving funds to initiate improvements.

Even with such strengthening of future applications, it is hard to foresee the full future value of the concept. Very clearly, many problems are slipping through the cracks with the current acquisition process. The concept of a formal phase for maturational development is one way to systematically address such problems. Applying the concept, of course, is not trivial. The cost for each application was $6 million for Stage 1, and each application would run from $200 to $250 million for full implementation of Stage 2. The next two sections address ways to reduce such costs in the future.

V. EXISTING INITIATIVES THAT CAN HELP REFORM AVIONICS ACQUISITION AND SUPPORT

One way to reduce the cost of maturational development is to reduce the number of problems that slip through the cracks in the development process. The Air Force already has several initiatives to reduce R&M deficiencies before the IOC date. Strengthening these initiatives is an integral part of our proposed strategy for reforming avionics acquisition and support. We see them as important complements to the maturational development concept. This section describes these initiatives, how they are intended to improve avionics R&M, and how they might be strengthened to increase their contributions.

The initiatives fall into two categories:

- Avionics technologies.
- Development procedures.

R&M-RELATED AVIONICS TECHNOLOGIES

The margin of combat superiority that our weapon systems enjoy over those of prospective enemies has largely resulted from our aggressive application of advanced electronics technologies to wartime needs. Recognizing our strength in this area, the Department of Defense has embarked on programs to accelerate this trend by introducing two new basic technologies that also have the potential to contribute to improved R&M:

- Very High Speed Integrated Circuits (VHSIC).
- Gallium arsenide circuits.

Two other technological developments are also underway:

- Electronically scanned antenna.
- Improved Built-in Tests.

The electronically scanned antenna may appreciably improve the reliability of fighter airplane radars and may lead to the replacement of the reliability-limited mechanically scanned antenna. Because many other avionics technologies will contribute to the R&M states for the next generation of fighter airplanes, we recommend that the Air Force review and accelerate other R&M-related avionics technologies.

The following discussion identifies opportunities that the Air Force can exploit to further strengthen the R&M benefit to be derived from these new technologies.

Very High Speed Integrated Circuits (VHSIC)

The use of VHSIC aims to increase digital processing capacity through further miniaturization of electronics, which will increase computing *speed* by shortening the paths that signals must traverse and increase computing *capacity* by packing more equipment in a given amount of space. The faster computations and greater number of computations per unit of volume promise not only greatly increased functional performance but also improved ease of maintenance and reliability.

Ease of Maintenance. VHSIC especially offers increased opportunities to track down Type B faults by capturing information about the equipment's environment, operating state, and test parameter values at the time of the failure. However, we find no evidence that VHSIC technology is being aggressively applied to facilitate collection and analysis of such information to support the detection or isolation of subsystem-level faults. Thus we recommend that the Air Force take measures to strengthen the application of VHSIC to improve subsystem-level BIT.

Reliability. VHSIC technology also offers opportunities to improve reliability because design and manufacturing goals for VHSIC chips are five times higher than those for existing integrated circuits, and placing more circuits on a single integrated circuit chip reduces the opportunities for failure at points where chips are connected to adjoining circuit elements. However, the miniaturization that gives VHSIC its vast computational prowess may also introduce risks that could cut short such projections. Miniaturization is reaching a point where some electrical elements in a chip are only 20 to 100 atoms thick. We recommend that the Air Force strengthen efforts that are exploring the ability of such chips to function over the 15- to 25-year service life of a combat airplane.[1]

VHSIC technology does not necessarily produce subsystem reliability. VHSIC technology will be applied mostly in those areas where digital processing is now performed. However, not all subsystems are dominated by digital processing,[2] and many of the ones that are will

[1]The Rome Air Development Center is currently sponsoring some research in this area.

[2]Those subsystems that pose the greatest R&M problems are not necessarily dominated by failure modes in the digital processing. For example, less than 30 percent of the removals for the F-15 and F-16 radars involve the digital processing LRUs. The oth-

experience great increases in it in the near future. Thus, the influence of VHSIC on subsystem reliability will depend on (1) the proportion of the subsystem type that already uses digital processing, (2) the increased volume of such processing that will be required in the next generation of equipment, and (3) the dominant failure modes that materialize when VHSIC technology meets the operational environment of the combat airplane.

Although these potential difficulties should not raise inappropriate alarm, experience with innovation has taught us that technological progress in electronics can introduce new failure mechanisms that need to be identified, diagnosed, and addressed before the equipment is mature. Such was the case when integrated circuits first replaced circuits constructed from transistors, diodes, etc. At that time, arguments for integrated circuits were similar to those for VHSIC: fewer elements and connections would improve reliability. Initially, however, integrated circuits led to lowered reliability because manufacturers did not recognize the need for a very clean manufacturing environment. In early integrated circuits, minute impurities caused molecular migration that corrupted the electrical integrity of the equipment. In addition, molecular migration can afflict much larger circuits, such as those in computers and in the F-16 radar's LPRF. In view of the speed with which the Air Force will be incorporating VHSIC technology in critical weapon systems, a strengthening of its efforts to identify and diagnose VHSIC failure modes represents an opportunity to assure that VHSIC contributes a considerable net benefit to R&M.[3]

Gallium Arsenide Circuits

Gallium arsenide circuits are intended to increase analog processing capacity the same way that VHSIC aims to increase digital processing capacity. Gallium arsenide technology has not, however, developed as far as VHSIC technology. We recommend that the Air Force especially pursue the identification and diagnosis of failure modes that may prove peculiar to gallium arsenide circuits.

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ers are in the analog and electromechanical portions of the radar. Thus there are limits to the R&M benefits derived from VHSIC.

[3]Time and again, development programs have fallen victim to what might be termed the "Titanic Syndrome." Expected to be invincible, equipment using new sophisticated technologies has unfortunately fallen prey to unforeseen faults. The Air Force can avoid catastrophic R&M "icebergs" only by improving our knowledge *in advance* about failure pathologies for critical new technologies. We define "failure pathologies" as the study of the essential nature of the conditions under which technologies tend to fail and the causes, timing, and consequences of these failures.

Reliability will improve if circuits can be kept at low temperatures. However, the need for lower temperatures places a larger demand on the airplane's environmental cooling system, which in turn increases weight and size. Consequently, we recommend that the Air Force carefully investigate tradeoffs between reliability improvements due to gallium arsenide and decreased performance due to greater weight and size. In addition, we recommend an aggressive test program to establish the correlation between incremental decreases in temperature and incremental increases in reliability. For R&M to fully benefit from the application of gallium arsenide technology, the Air Force needs to strengthen ongoing research to provide a sound technical base from which future designers can make appropriate tradeoffs.

Electronically Scanned Antenna

An electronically scanned antenna for a fighter airplane would have an array of up to 2000 electronically active elements. Each active phased array element provides the equivalent of a radar antenna, transmitter, and receiver. The collection of elements provides an electronically steerable antenna that replaces a mechanically scanned antenna. An active phased array will do away with elements in current radars that are prone to failure: (1) the transmitter with its high power elements, and (2) the mechanical and hydraulic elements constituting the antenna. It offers two benefits:

- Improved radar performance because of the more rapid scanning it allows.
- Improved R&M because it replaces equipment that currently limits radar R&M.[4]

Such an antenna could provide considerable benefits. However, considerable development challenges also remain in this area. Because of the currently limited scope and amount of research and development efforts sponsored by the Air Force in this area, we recommend an acceleration of such efforts. By strengthening research and development of an electronically scanned antenna, the Air Force may be able to more quickly identify the most important R&M challenges with this important new technology. The sooner such challenges are defined, the sooner engineers can develop sound technical approaches for dealing

[4]There is also the opportunity for graceful degradation of performance as elements in the array experience various types of failures because the failure of a few random phased array elements does not materially affect radar performance. Some failure modes may lead to more rapid degradation in performance than others. An extreme case would be where many neighboring elements failed together.

with them, and the fewer the problems that will remain for cleaning up during a maturational development phase.

Improved Built-in Tests

Another area needing increased Air Force attention is BIT technology. Unlike pilots and maintenance personnel, the avionics industry and the Air Force generally fail to see the full limitations of BIT. They also fail to see its great unfulfilled potential. Avionics contractors know little about the strengths and weaknesses of competing BIT mechanizations and even of displays for BIT results. Indeed, our experiences have shown that key people at Westinghouse do not fully understand Hughes's approach to BIT and that people at Hughes do not fully understand Westinghouse's. In addition, no Air Force organization oversees BIT development. Thus the Air Force knows neither the current state of the art nor the basic research needed to advance it.

The Air Force especially needs to accelerate BIT technology to deal more rapidly and accurately with Type B faults. As a consequence, we propose a special project—with priority for expedited research—to assess the state of the art, sponsor research, and establish design guidelines. Design guidelines could include design allocations for BIT, sensors, circuits, and computer memory, and processing. Most important, BIT mechanizations need to capture more fully the state of the subsystem when a fault occurs, thus capturing key system parameters, switch settings, and operating environment conditions. Strengthening the Air Force's initiatives directed toward BIT technology is a major opportunity for improving the capability of the support process to address Type B faults.

Other Avionics Technologies

To better prepare other avionics technologies targeted for the Air Force's next generation of fighter airplanes, it is instructive to examine the approach being taken with propulsion technologies. The Engine SPO is currently managing or coordinating the execution of programs aimed at cultivating critical technologies, testing them in exploratory development tests, and maturing them in advanced development programs. Similar work is needed for avionics. In the past, advanced turbine engine gas generators were built and tested to pave the way for subsequent full-scale engine development. Such components are usually built to represent the expected approximate size required for the target application engine. These advanced designs then go through further changes once the final engine size has been determined.

Because it is not benefiting from such a degree of organized attention, avionics technology—also crucial to the next fighter—faces two serious challenges:

- The Air Force needs to review the status of critical technologies, especially radar and ECM, and identify ways of accelerating these technologies to benefit R&M.
- The Air Force needs to sponsor more efforts devoted to building advanced development components using the basic technologies that the Avionics Laboratory and avionics industry have been cultivating.

Such components can then receive the kind of performance and durability testing that critical engine components now receive. By so doing, the Air Force can accelerate the maturation of technologies and equipment, which will help reduce the number of problems that would arise during a maturational development phase.

R&M-RELATED DEVELOPMENT PROCEDURES

In addition to the foregoing technology initiatives, the Air Force is also examining new procedures aimed exclusively at improving the ease of maintenance and reliability for avionics equipment. This subsection identifies ways that three of these procedures could be strengthened to make an even larger contribution to improved R&M. The procedures address:

- Modular avionics.
- Ultra-reliable avionics.
- Avionics integrity.

Modular Avionics

Modular avionics aims at developing smaller and cheaper LRUs, which in turn would negate the need for an avionics shop. The whole intermediate level of maintenance might be eliminated.

Current LRUs are so costly, removed so often, and in such short supply that each airbase generally needs its own avionics shop. Because many LRUs cost between $100,000 and $1,000,000, the avionics shop uses large sets of test equipment to identify faulty SRUs within these LRUs. The shops then send these less expensive SRUs to the depot for repair, which reduces the time and the value of assets tied up in the support pipeline.

To eliminate the need for avionics shops on airbases, the avionics industry and various Air Force organizations are examining the concept of modular avionics.[5] Rather than building a radar with five to nine LRUs (see Figs. 4.1 and 4.8), these efforts aim at building a radar with 50 to 100—or perhaps more—modules. Like LRUs, these modules could be removed at the flightline; like SRUs, these modules would be fairly cheap and could be sent to the depot for repair.

The successful development of modular avionics faces two major technical hurdles:

- Packaging the modules to withstand the flight and flightline environment.
- Designing BITs to isolate faulty modules accurately.

Packaging Modules. Flightline maintenance personnel must be able to remove faulty electronics equipment quickly from airplanes not only in shelters behind closed doors but also outdoors and exposed to wind, rain, snow, dust, and even sand. Most electronic circuits need protection from such environmental elements. Current LRUs are protected by closed metal containers that are only opened inside the environmentally controlled avionics shop. For modules to work, they also need containers to protect them from the environment, i.e., from wind, rain, snow, dust, and sand, and this will inevitably add to the airplane's weight, volume, and environmental cooling needs. In addition, these packaged modules need to be plugged into the airplane. Certain types of connections, such as those for the F-16 radar's LPRF unit, are especially demanding in terms of alignment, firmness of fit, and freedom from contamination. Increases in the number of such connections and in the environmental stresses placed on such connections will potentially make the avionics equipment more vulnerable to the flightline environment.

Designing BIT. Although this concept of sending smaller modules to the depot is economically very attractive, even avionics shops with their large sets of extremely sophisticated equipment currently experience problems in identifying the correct SRU to send to the depot. About one out of every five SRUs sent to the depot has no failure evident when tested on the depot's test equipment.[6] To avoid the need for an avionics shop at each airbase, adequate amounts of BIT need to be designed to isolate the faulty modules and faulty connections between

[5]These efforts include an Air Force Avionics Laboratory program known as PAVE PILLAR, an Air Force Air Staff effort known as Modular Avionics System Architecture, and various industry efforts known as Line Replaceable Modules.

[6]Sending the wrong module to the depot is only one of many reasons for this level of performance.

modules. Moreover, some way must be found to deal with faults that are not detected and isolated by the BIT down to the module level.

Some types of electronics, such as digital processors, may be more amenable to modular avionics. Other types, such as those with delicate radio frequency connections and large amounts of analog circuitry, may be less amenable because their faults are so difficult to isolate.

To enhance its decisionmaking about modular avionics, we recommend that the Air Force initiate special efforts to better understand:

- Increases in an airplane's weight, volume, and environmental cooling system (ECS) caused by modular avionics.
- Requirements for connecting modules under a broad range of operating environments.
- Ways in which technology can provide necessary levels of fault isolation, especially in modules that use analog circuits or that can suffer from Type B faults.

Although research is lacking or is proceeding slowly, modular avionics have the potential to affect avionics R&M for better or for worse. It is important therefore that a sound technical base be developed to support future decisions in this area. To that end, we see a need for the Air Force to strengthen its research and development in this area, especially from the standpoint of maintainability.

Ultra-Reliable Avionics

The development of ultra-reliable avionics equipment aims at producing an MTBF of from 2,000 to 10,000 hours for major subsystems. This advance would greatly reduce the need not only for fault isolation but also for maintenance at all levels of the support process. To achieve ultra-reliable avionics, the Air Force is looking to VHSIC and gallium arsenide technologies and modular avionics.

Expectations of achieving ultra-reliable avionics create a potentially dangerous environment for improving maintainability. If we had high assurance that such subsystems as radars, infrared search and track sets, ECM, and weapon delivery could achieve ultra-high levels of reliability, then we would be more sympathetic to the resulting reduced emphasis on maintainability. However, our previous discussions of VHSIC, gallium arsenide circuits, and modular avionics have raised enough questions to cause concern about placing too much hope in ultra-reliable avionics without adequate attention to fault isolation.

The Air Force needs to strengthen these efforts by also requiring a balanced emphasis on ultra-maintainability.

Avionics Integrity Program

The Aeronautical Systems Division has been working on a plan for a program that would apply to avionics the principles underlying its Structural and Propulsion Integrity Programs. These principles are embodied in a three-step process that involves:

1. Measurement of the time-varying stresses and temperatures in the operating environment.
2. Determination of the maximum size of imperfections that may reasonably be expected to escape detection during manufacturing and be tolerated without degrading functional performance.
3. Estimation (with models of physical processes) of the hours of operational service that would have to occur before imperfections that escaped detection during manufacture could degrade needed functional performance.

How well might these principles be applied to avionics?

Engineers need better information about the time-varying stresses and temperatures that avionics equipment actually experiences. In a combat environment, fighter airplane avionics probably operate at higher temperatures and under wider and more rapid swings in temperature and g loads than any other application of electronics. These environmental conditions tend to shorten the life of electronic components. The high temperatures result from the large amount of avionics equipment, the weight and volume penalty caused by increasing the size of the ECS that cools the avionics, and the added drain on valuable propulsion power that a larger ECS would impose. The high g loads in a fighter can rip apart a connection that has been weakened through cyclic stresses from vibration and time-varying g loads and thermal gradients.

The wide and rapid swings in thermal and g loads are especially acute in combat-maneuvering fighter airplanes that dive and climb between very cold high altitudes and very warm low altitudes. In many systems, the most taxing environmental condition is a rapid dive from a high altitude followed by a high speed dash at sea level on a hot and humid day. The airplane is being buffeted by aerodynamic forces, and the ECS is combating not only internally generated heat from electronics but also the warm ambient condition outside the airplane. Meanwhile, it is "raining" inside the avionics bay because of moisture condensation. At least at high altitudes, the cold outside temperatures can help the ECS keep the electronics somewhat cooler and free of moisture-induced corrosion.

Designers try to take all such factors into account when designing electronics. They use handbooks and generic specifications to define a baseline characterization of the operating environment. What is lacking in avionics design—and used to be lacking in structures and propulsion design—is a follow-up data collection effort to characterize the actual operating environments. This follow-up for structures and propulsion has shown that the actual operating environments were far harsher than the baseline characterization used for design; furthermore, such environments were shortening the functional life of key components.

Because avionics design may experience similar problems, the ASD plan to require routine monitoring of temperature and stress could be highly beneficial to controlling future design choices regarding heat dissipation features and required ECS capacities. It should add only small marginal costs.

Although the first basic principle underlying the Structural and Propulsion Integrity programs appears to have directly beneficial relevance to avionics, it is less clear that the other two will be as helpful, especially for leading-edge technologies where designers are applying recent technological advances for the first time. Some degree of operational experience is often required before the operationally dominant failure modes and failure physics are understood well enough to support analytic modeling and engineering evaluation during the design process. Because electronics equipment uses many different materials and manufacturing processes, we still lack much information about manufacturing impurities, their critical sizes, and the rates at which they enlarge and migrate when subjected to different time-varying stresses.

For mechanical failure modes of well-known technologies, the kinds of combined thermal and stress analysis advocated by the Integrity programs certainly need to be extended to avionics. The appropriate approach for other failure mechanisms—such as chemical processes, connector problems, and system faults—is less clear.

The primary means that the Air Force has to strengthen the contributions of the Avionics Integrity Program (AVIP) toward improved R&M are

- Accelerate efforts to characterize actual operating environments.
- Expand AVIP to include research into the potential linkage between time-varying environmental conditions and the time-varying symptoms of some Type B faults.

Such actions would help advance the state of knowledge regarding the phenomenon of the Type B fault and its influence on maintainability.

Summary

New technologies such as VHSIC, electronically scanned antennas, and gallium arsenide, and new procedures such as modular avionics, ultra-reliable avionics, and the Avionics Integrity Program can all help improve avionics R&M. Moreover, by strengthening ongoing work in each of these areas, the Air Force can further improve avionics R&M. We see such strengthening as an important part of an overall strategy to reform avionics acquisition and support.

Even with strengthened initiatives we must keep our expectations in perspective. We need time to acquire engineering data, develop analytic methods, and institute necessary guidance. Perhaps quantum improvements in reliability will prove attainable and affordable even in the fighter airplane environment, and perhaps someday such improvements will regularly be achieved. Meanwhile, we continue to need improved maintainability, including the development of more effective BIT. Thus far, the current Air Force activities described in this section have not addressed ease of maintenance with the same depth that they have addressed reliability (see Table 5.1). A more balanced approach is needed that emphasizes *both* reliability and maintainability. One way to help provide that balance is the maturational development concept that was discussed in Secs. III and IV.

Table 5.1

SUMMARY OF THE RELATIVE POTENTIAL CONTRIBUTIONS FROM CURRENT AIR FORCE INITIATIVES

	Reliability		Maintainability	
Current R&M-Related Initiatives	Type A faults	Type B faults	Type A faults	Type B faults
Technologies				
VHSIC	+++	+	+	+
Gallium arsenide circuits	+++	+		
Electronically scanned antenna	+++	+	+	
BIT		+		+
Other fighter avionics	+++	+		
Development Procedures				
Modular avionics[a]				
Ultra-reliable avionics	+++	+		
Avionics integrity program	+++	+		

NOTE: Plus signs (+) denote relative degrees of expected contribution. Three (+++) denote a greater expected contribution than two (++).

[a]The contribution from modular avionics lies mainly in the reduced cost of the flightline-removable module and the opportunity to avoid having an avionics shop at the base. The real problem with current avionics involves isolating faults to the proper module.

VI. NEW INITIATIVES NEEDED TO HELP REFORM AVIONICS ACQUISITION AND SUPPORT

To help address the major weaknesses in the processes for avionics acquisition and support (Sec. II), the preceding sections have proposed a complementary combination of instituting maturational development and strengthening certain initiatives that the Air Force has already undertaken. Two further initiatives would provide the Air Force with major additional steps toward implementation of a comprehensive strategy for reshaping its processes for avionics acquisition and support. To complete this strategy, we recommend that the Air Force:

- Institute Performance Oriented Tracking of Equipment Repair (PORTER).
- Reorganize its avionics engineering resources.

These initiatives could help ensure a balanced approach to avionics acquisition and support, one that appropriately concentrates on both reliability and maintainability. They also could go a long way toward making maturational development a more cost-effective process.

INSTITUTE PERFORMANCE ORIENTED TRACKING OF EQUIPMENT REPAIR (PORTER)

This initiative has the potential to

- Greatly increase the capability of maintenance technicians to identify equipment that the shop or depot has failed to restore to full designed capability.
- Considerably reduce the cost of collecting data for Stage 1 of maturational development.

A prototype has already demonstrated many of the functions essential to a full mechanization of the PORTER concept. The Air Force currently is exploring the possibility of instituting the PORTER concept within its recently developed Core Automated Maintenance System (CAMS).

This subsection defines the problem that PORTER was conceived to address, discusses the PORTER concept, describes the evolution of the prototype, reviews some preliminary results, and proposes a plan for instituting the PORTER concept.

Problem

Even with the best engineering efforts—including a formal process aimed at maturing reliability and maintainability—some avionics faults will still evade detection and correction at various points in the support process. The experimental prototype system known as PORTER aims at providing information needed to track down such faults, fix them, and in so doing document the deficiencies in the support process that allowed these faults to escape detection in the first place.

Faults in avionics equipment can escape detection for many reasons. On the one hand, the narrow confines of the airplane and the limitations of BITs make it impossible to test all equipment thoroughly when the airplane is in the air. On the other hand, the inability to replicate airborne stresses makes it impossible to test all equipment realistically when the airplane is on the ground. Moreover, when equipment is removed from the airplane and taken to shops and depots for more exhaustive testing, both the nature of the tests and their pass/fail criteria change.

Because of the complexity of the avionics equipment, tests often inadvertently leave gaps in their coverage. Consequently, faulty equipment circulates through the support system until either the fault develops into a more serious problem or maintenance personnel take extraordinary measures to isolate the problem. Such repeated circulation of faulty equipment occurs all too frequently with sophisticated airborne electronics equipment.

When an item of equipment circulates in this fashion, it is commonly labeled a "bad actor." These must be eliminated because they deny pilots regular and dependable access to the equipment's full designed capability. Fixing them involves extra effort on the flightline, in the shop, and at the depot. Bad actors must be located and the LRUs must be then sent to the depot for special repair action so that airplanes are as completely rid of them as possible and are restored to their full combat capability. Eliminating bad actors will reduce the extraordinary maintenance effort on the flightline, in the shop, and at the depot, but most important, it will provide pilots with equipment that can dependably deliver its full designed capabilities.

Unfortunately, the Air Force's standard data systems do not gather sufficient information from flight-to-flight performance to enable maintenance personnel to identify and diagnose ineffectual maintenance and evolving problems with sophisticated avionics. PORTER attempts to fill this gap.

The Concept of PORTER

PORTER's primary purpose is to be a maintenance aid. It aims at reducing avionics maintenance burdens—especially for such sophisticated equipment as fire control radars—through judicious collection and timely transmission of performance and maintenance information to critical points in the support process. This information should enable maintenance personnel to identify and quickly fix equipment that otherwise circulates repeatedly through the support process, using up time and scarce resources. Figure 6.1 shows how maintenance information currently flows, and Fig. 6.2 shows how it would flow after PORTER were instituted.

Ultimately, the use of PORTER should increase the number of weapon systems prepared to deliver their full designed capability. Thus, the philosophy underlying PORTER is to increase combat effectiveness by decreasing the burden on personnel, spare parts, and test equipment.

For PORTER to work, the perceived value of its services must exceed the costs imposed by its record-keeping demands. Thus, every

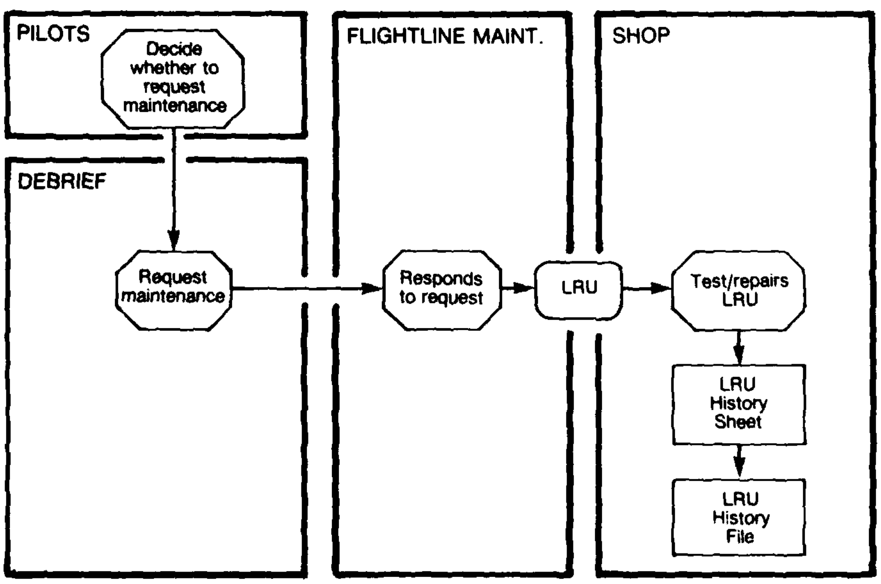
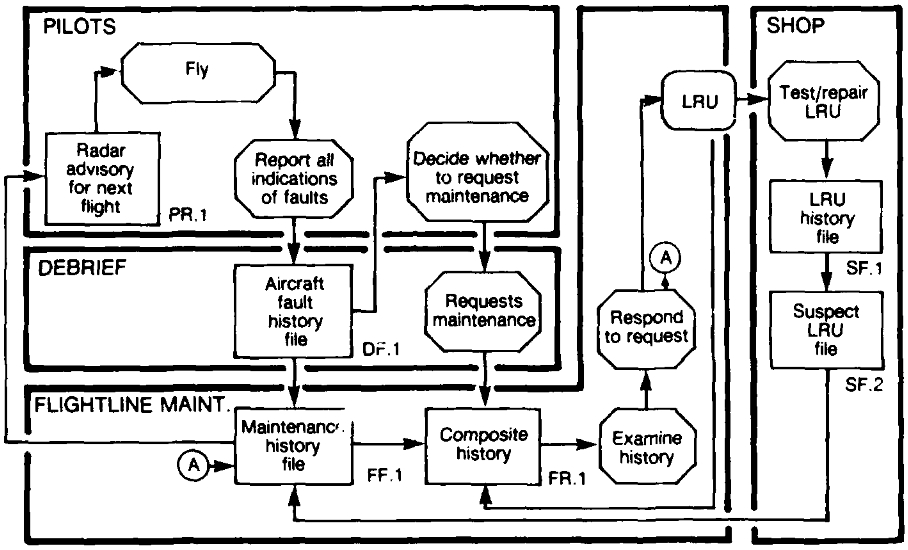


Fig. 6.1—Current maintenance information flow



NOTES: DF.1, FF.1, SF.1 and SF.2 are computer files.
PR.1 and FR.1 are printed reports.

Fig. 6.2—Maintenance information flow after instituting PORTER

supplier of information should receive a directly beneficial product that logically depends on the information he supplies (see Table 6.1). For example, although the pilot would spend slightly more time in maintenance debrief, he would receive a preflight advisory that will make him more aware of potential problems with his airplane and enable him to make more effective maintenance requests.

Although PORTER should provide uniquely useful maintenance information for product improvement, its primary goal is to serve as a maintenance tool, not as a data system. This goal places serious constraints on PORTER's development. It must be highly synchronized with actual events in the maintenance process. To accomplish this, an operational squadron has been closely involved not only in testing and debugging the prototype for PORTER, but also in defining and experimenting with its specifications.

Table 6.1

PORTER'S PRODUCTS AND BENEFITS

Supplier of Information	Product Received	Benefit Perceived
Pilot	Preflight advisory	Sit·.tion awareness
	Postflight fault history	More effective maintenance requests
Debriefer	Fault history by subsystem	Fewer fault entries due to more timely maintenance requests
Flightline Maintenance	Composite history of faults, maintenance actions, and resident LRUs	Fewer LRU removals due to more rapid fault isolation
Shop Maintenance	Composite history of LRUs	Quicker case development for bad actor LRUs

Evolution of the PORTER Prototype

When the results of the F-15/F-16 Radar R&M Improvement Program were briefed during October 1985 to Headquarters United States Air Forces in Europe (USAFE) and the 36th TFW at Bitburg, audiences were receptive to the recommendation concerning detailed debriefing of pilots and tracking of equipment by serial number. Consequently, a prototype development and demonstration of PORTER was instituted at Bitburg. This effort had two main objectives:

- D.;monstrate an initial PORTER capability at Bitburg Air Base.
- Suggest how specifications for future Air Force data systems might include PORTER-like services.

Because the prototype development and demonstration effort was conceived as a short-term, quick-response project, it did not enjoy the benefits of an in-depth research project that could have explored alternative architectures, hardware, and software approaches. The project had the advantage, however, of a joint development enterprise that includes technicians in the field—the people PORTER would serve.

The PORTER prototype was conceived as a personal-computer-based (PC) tool to help maintenance technicians. Whether it would help, and whether it would be used, depends on how maintenance personnel would use PCs to enter, transmit, and extract data. Success of the PORTER prototype, therefore, depends on finding ways for PCs to:

1. Accommodate the breadth of subsystems, the depth of information, and the amount of history that maintenance technicians would require.
2. Overcome the slowness with which standard database packages extract information from large databases.
3. Store large amounts of information economically when relevant data forms are either mostly blank or (less frequently) contain large amounts of useful information.
4. Efficiently transfer information between maintenance levels (cockpit, debriefing, flightline, shop, and depot).

USAFE added a fifth challenge in response to their concern about a prospective enemy's gaining access to information that would reveal weaknesses in combat capability:

5. Provide adequate protection (e.g., encryption) for sensitive data.

More recently, a sixth challenge is emerging with the incorporation of the Core Automated Maintenance System (CAMS) at Bitburg during the summer of 1987:

6. Interface and integrate a PORTER capability with CAMS to avoid duplication of data entry tasks and equipment.

Preliminary Results

The prototype has thus far met challenges 1, 2, and 5[1] and thereby provided Bitburg with a limited initial capability and the Air Force with some initial ideas about potential specifications for enhancing CAMS.

With this initial capability, the 36th TFW at Bitburg has developed a database that is being used to

- Identify LRUs with histories of repeated visits to the shop.
- Develop documentation packages that are being sent to the depot whenever such an identified LRU is sent to the depot.

Thus far three such LRUs and associated documentation packages have been sent to the depot at the Warner Robins ALC.

[1]Challenge 5 was satisfied by using TEMPEST qualified PCs and by using floppy disks to manually pass data between locations on base.

Example 1. The first of the three LRUs left Bitburg's avionics shop on December 13, 1986. During May 1987, it finished receiving depot repairs and was on its way back to the field. It is a unit that

- Accumulated 52 operating hours (approximately 40 flights) while installed on various aircraft during 1986.
- Would intermittently fail either the "blanking gate" BIT or the "RF No Go" BIT while installed on various aircraft during 1986.
- Made nine visits to the base avionics shop during that time, where an additional 75 operating hours were accumulated.

At Bitburg, a Hughes technical representative helped the shop technicians in their attempts to repair the LRU. When the unit arrived at the depot, the technicians undertook extraordinary measures to try and fix the unit:

- They ran the unit for two days on the AIS test equipment[2] before they detected and isolated the first failure ("blanking gate") to an SRU. Shortly thereafter they detected and isolated faults consistent with the RF No Go failures. These faults were located on two other SRUs.
- After replacing these three SRUs, they then installed the unit on the subsystem bench[3] and ran 150 iterations of the portion of the BIT that tests this unit to further verify their repairs.

Whether the depot's very considerable efforts have finally fixed this unit will not be known until it reenters operational service at some air base. In an attempt to follow up on the performance of the LRU, a note on a tag tied to the unit asks the base that receives it to contact a person at the depot so that technicians can track the unit's performance. (If all F-15 bases had a PORTER capability, such tracking would occur almost automatically.)

Example 2. This unit left Bitburg's avionics shop on April 6, 1987, and arrived at the depot's repair line on May 29, 1987, with its complete complement of PORTER documentation showing that the unit

- Accumulated 56 operating hours (approximately 40 flights) while installed on various aircraft during 1986.

[2]Using the same type of test equipment and the same tests as used at Bitburg's avionics shop.

[3]The shop at Bitburg does not have a subsystem bench. Such a bench is a complete radar subsystem, with some associated test equipment, that provides a subsystem-level environment for testing. The shop's test equipment only tests LRUs individually, in isolation from the rest of the radar subsystem.

- Made six visits to the shop during that time, where an additional 16 operating hours were accumulated.

The depot was working on this unit at the time of publication of this report.

Example 3. This unit left Bitburg's avionics shop on January 22, 1987. The Hughes technical representative at Bitburg alerted the depot that this unit was on the way. The PORTER documentation showed that the unit

- Accumulated 18 operating hours (approximately 15 flights) while installed on various aircraft during 1986.
- Made seven visits to the shop during that time, where an additional eight operating hours were accumulated.

Unfortunately, the unit went through the depot's standard LRU repair procedures and left the depot before anyone realized that it was a PORTER item. The depot's limited documentation does not reveal the nature of the depot's repair action. Moreover, the lack of a worldwide PORTER capability means that we cannot follow up on the unit's performance at its next air base.

A Plan for Instituting PORTER

A general implementation of PORTER has the potential of helping maintenance technicians better maintain the sophisticated kinds of electronics that are now an integral part of nearly every type of aircraft that the Air Force now operates. We propose, therefore, that the Air Force institute PORTER in a manner that gives it the option to install a PORTER capability initially at the bases in greatest need and then later at other bases.

As PORTER is applied to different weapon systems, the software will need to be tailored to accommodate differences in

- The complement of subsystems that constitute the weapon systems.
- The pods that the weapon systems carry.
- Failure indicators (including BIT) for subsystems.
- Maintenance parameters peculiar to a specific subsystem.

The prototype software in use at Bitburg for the F-15 cannot be used, for example, on the F-16, F-111, etc. This leads to challenge number 7 for implementing PORTER:

7. Tailor the software for an individual weapon system.

The Proposed Architecture. One way to meet the seven challenges is to use PCs to simultaneously provide

- PORTER services.
- Data entry and extraction terminals for CAMS.

The PCs could be placed at seven locations, as they are now with the prototype at Bitburg: pilot debriefing (three locations, one for each squadron), *flightline maintenance* (three locations, one for each squadron), and the avionics shop.[4] The PCs would need to communicate with one another and with the CAMS software that is now hosted on a mainframe computer (the Sperry 1100).

An Alternative Architecture. Another way to meet the seven challenges is to build the PORTER services into the CAMS software that would be hosted at a centralized location(s). With this architecture, user locations could be served by dumb terminals. There would be no need for PCs. There would be no need for maintaining PC software. There would be no need for communication links other than the direct links to the CAMS centralized location(s). Although these are certainly attractive features, the prospective disadvantages are

- Time required for software development.
- Time required to adapt software to the evolving definition of PORTER services.
- Loss of air base flexibility to tailor PORTER services.
- Potential nonavailability of the CAMS centralized location(s) because of deployment or enemy attack on the air base or other problems at the centralized location(s).

Current CAMS Architecture. Another approach is to incorporate as much of the PORTER services as possible within the current CAMS architecture. The Air Force plans a test of this approach during the summer of 1987 at Tyndall Air Force Base. This approach would give the Air Force a nearly immediate capability. The prospective disadvantage is that only a small portion of the PORTER services may be provided. The summer 1987 test needs to help answer three questions: (1) How much of the PORTER concept can be delivered quickly by merely adding an analysis package and retrievals to the current version of CAMS? (2) How far does such a quick mechanization go toward giving the Air Force the information management capability that it needs to effectively identify and repair bad actor equipment? (3) Is further progress needed?

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[4]For the avionics shop, it probably would be worthwhile to have three PCs: one for the automatic test stations, one for manuals, and one for the TEWS test equipment.

Recommendation. In the event that the answer to question three is yes, and in view of the reality that the test may take longer than expected to complete, we recommend that the Air Force concurrently begin preliminary definition for the Proposed Architecture and also review the Alternative Architecture as a backup.

There are two justifications for such an accelerated effort: (1) the value in combat from increased readiness of full designed capabilities, and (2) the opportunity to appreciably reduce the cost of collecting the data needed for Stage 1 applications of maturational development. Much of the $6 million cost for assessing the R&M situation for each radar (Sec. IV) was accounted for by the 17 data collectors at each air base. If those bases had a PORTER capability already resident and in full use, the number of data collectors could have been considerably reduced. Early instituting of PORTER, therefore, can make Stage 1 of the maturational development concept more affordable sooner and increase the overall effectiveness of the concept.

REORGANIZE AVIONICS ENGINEERING RESOURCES

The overall effectiveness of maturational development is also influenced to a very great degree by how the Air Force applies its limited avionics engineering resources. From the previous sections one can infer several difficulties with the application of these resources. After reviewing the more dominant difficulties, we set forth a proposal for reorganizing the application of these resources.

Difficulties

Diffusion of R&M Responsibilities. Diffusion of R&M responsibilities occurs throughout the acquisition process. It becomes especially acute when the Weapon System SPO starts anticipating PMRT. By its very nature, the advent of PMRT forces the Weapon System SPO to start closing out its engineering responsibilities. It is therefore the wrong time to start new R&M improvement initiatives. Moreover, once PMRT occurs, responsibility for an avionics subsystem passes to one organization and responsibility for the shop's intermediate test equipment passes to an entirely different one, usually located at a different air base.

Lack of a Single Organization to Manage Implementation of Improvements. For the ongoing efforts to mature the F-15 C/D radar and the F-16 A/B radar, the ASD Strike SPO was made responsible for the Stage 1 assessment of the R&M situation, but no single organization bears responsibility for coordinating Stage 2 (implementation of improvements) for either radar. The Strike SPO has helped fill the gap on several of the generic improvements. However, resource limitations of the Strike SPO together with personnel limitations at the depots have constrained the extent of this involvement and thus restricted the pace of the implementation.

Not Allowing Depots to Use Development Funds to Undertake Engineering Development of Improvements. One limitation at the depot is the policy of not allowing depots to spend development funds (so-called 3600 money) to fund engineering development of needed improvements. This has hindered development of a new LPRF unit for the F-16 A/B radar. Where exceptions to this policy have been allowed, progress is now being made.

A Model for an Avionics Engineering Center

Avionics engineering resources should be reorganized to address the foregoing difficulties and to improve the Air Force's ability to implement the proposals put forth in this report. One way to do this would be to create an Air Force Avionics Engineering Center along the lines of the following model.

The Center would provide broadly ranging expertise and corporate memory, including detailed knowledge of forthcoming threats, R&M problems in the field, ongoing development efforts, and potential roles for emerging technologies. It would apply such a knowledge base and its engineering expertise to Air Force avionics efforts ranging from advanced basic research through maturation of fielded equipment.

The Center would have primary responsibility for managing and coordinating both Stage 1 (Assessment) and Stage 2 (Implementation of Improvements) of maturational development.

The Center's primary objectives would be to

- Develop advanced plans to meet future needs.
- Formulate guidance for Air Force and industry research.
- Review the allocation of resources to laboratory programs relating to avionics.
- Manage advanced development of critical components, subassemblies, and prototypes for future subsystems.
- Manage development of avionics subsystems that are applicable to multiple weapon systems.
- Manage development of avionics subsystems for major weapon systems in those situations where the weapon system SPO chooses to assign management responsibility to the Center.

- Manage R&M maturation programs for selected subsystems.

Secondary objectives for the Center would be to assist:

- Weapon system development programs.
- Product improvement programs.
- User formulation of statements about forthcoming needs.
- Development of advanced concepts.
- Threat assessments.

As envisioned here, the already sizable Avionics Laboratory would continue to focus on advanced research and would operate separately from the Avionics Engineering Center. Although operationally separate, the laboratory's planning function would benefit from the Center's planning activities. Moreover, the Center would review the allocation of funds for the laboratory's advanced research programs. To minimize the opportunities for conflicts of interest, funds for advanced research should remain separate from funds that the Center would apply to its own programs.

To accomplish the foregoing objectives, the Center would need to undertake activities within four major areas:

- Field assessment.
- Technology management.
- Development management.
- Planning.

Field Assessment Area. Activities in this area would acquire, archive, and distribute information about R&M deficiencies being experienced in the field. This area would be a key source of information for each of the three other major areas. To fully accomplish its purpose, this area would need to launch and support efforts aimed at five objectives:

1. **Manage data collection and analysis.** Activities that would support this objective include managing Stage 1 (Assessment) of maturational development and routinely extracting relevant information about field problems from the Air Force's standard data systems.

An initial high priority activity could be Stage 1 assessment programs for the APG-68 radar used by the F-16 C/D and the ALQ-131 Block 2 electronic countermeasures pod.[5]

[5]Of the candidates identified in Sec. III, these are the ones that have recently entered production, hence the urgency to get started with Stage 1.

2. **Archive and distribute information.** Activities that would support this objective would include distilling lessons learned from Stage 1 maturational development programs, archiving such information, and distributing it in an appropriate format. Distribution should include SPOs, contractors, and appropriate laboratory programs.[6]

An initial high priority activity would be to archive and distribute information from the exploratory radar applications discussed in Sec. IV.

3. **Improve data systems support.** Activities here would include developing and supporting special data collection procedures to support Stage 1 applications of maturational development, and specifications for needed improvements to Air Force standard data systems such as CAMS.

Initial high priority activities would be to establish procedures for collecting engineering data on support equipment and to improve PORTER's analysis procedures to support applications to Stage 1 maturational development activities.

4. **Improve application of test and evaluation resources.** Two activities are essential here: improving airborne and ground-based test and evaluation resources and scheduling available assets.

High on the priority list should be the development of facilities to evaluate operational radars and to measure environmental parameters within avionics subsystems. The former facility could support a radar evaluation program aimed at operational evaluations of radar effectiveness.[7] The latter facility could support the development of essential databases for the AVIP program.[8]

5. **Coordinate field assessment programs.** Coordination would need to occur in three directions. Lateral coordination would be needed for Technology Management, Development Management, and Planning, and product improvement programs to assure that

[6]To a certain degree, the Air Force Acquisition Logistics Center is doing this at the weapon system level. An Avionics Engineering Center would be expected to pursue these activities to a far greater depth.

[7]Such a program might be modeled after the Air Force's Electronic Warfare Evaluation Program at Eglin Air Force Base.

[8]See Sec. V for a discussion of AVIP.

the Field Assessment area understands the needs of the other areas and the opportunities to contribute. Upward coordination would be required to secure adequate personnel and funding resources. Internal coordination within the area would be required to schedule resources against priority needs.

Technology Management Area. The purpose of this area would be to assimilate information about evolving threats, R&M deficiencies, and emerging technologies and use such knowledge to manage the development of technology from basic research through subsystem prototypes. This area would use information from the Field Assessment and Planning areas and indirectly would be a major supplier of technology for the Development Management area. To fully accomplish its purpose, this area would need to launch and support efforts aimed at four objectives:

1. **Evaluate technology development programs.** Accomplishing this objective requires periodically reviewing technology development programs and their progress in light of needs—both performance and R&M—and in consideration of alternative approaches. The Air Force's portfolio of such programs would need to be evaluated for balance across four major divisions (basic research, critical component development, advanced assemblies, and prototypes). A review of investment balance—in light of needs—would also be needed within each division.

An initial high priority should be assigned to a review of programs in the critical component development division, with emphasis on the needs of next generation fighter airplanes.

2. **Manage selected technology development programs.** This objective is aimed at important programs that—for whatever reason—fall outside the purview or interests of the laboratory. An example of such a program might be the development of critical components as a prelude to a full-scale engineering development effort. Another example might be the development of a prototype subsystem or assembly such as an antenna.

Two high priority activities could be competitive development of alternative designs for an active phase array element (critical component) and competitive development of alternative designs for an electronically scanned antenna based on such elements (Sec. V).

3. **Improve test and evaluation resources.** To adequately evaluate progress made by technology development programs, it

is often necessary to develop or acquire special resources for test and evaluation. Activities here would provide such resources.

4. **Coordinate technology development programs**. As with the Field Assessment area, this area also would require lateral, upward, and internal coordination. Such coordination is especially crucial to assure the relevance and value of the products of technology development programs. An additional dimension of coordination here is the opportunity to help guide industry's internal research and development efforts.

Development Management Area. The purpose of this area would be to assimilate information about evolving threats, R&M deficiencies, and developed technologies and use such knowledge to help manage avionics development, including product improvement. In addition to the airborne equipment,[9] the scope of involvement would include ground support equipment, maintenance instructions (TOs), and training. This area would be a major consumer of information from the three other major areas: Field Assessment, Technology Management, and Planning.

To fully accomplish its purpose, this area would need to launch and support efforts aimed at seven objectives:

1. **Formulate and maintain development guidelines**. Activities aimed at this objective include development and maintenance of standards (Military Specifications) and processes (AVIP; see Sec. V). They also should aim at appropriate distribution of information about R&M lessons learned in related programs.
2. **Assist SPOs in managing weapon system or subsystem development**. Here the main activity would be supplying knowledgeable engineers to support SPO programs, especially program reviews. The goal would be to supply engineers with experience in at least Field Assessment and Technology Management.
3. **Manage any avionics subsystem developments not assigned to SPOs**. Management of development for certain avionics subsystems is done directly by the Air Force. Those programs not assigned to SPOs could become activities within the purview of this objective.
4. **Manage and coordinate Stage 2 of maturational development**. The main activities would be managing and coordinating

[9]The word equipment and subsystem are always intended to include both hardware and software.

Stage 2 of maturational development. For a given subsystem, an activity would manage and coordinate the implementation of the improvement package that the Air Force selects from the Stage 1 effort.

Initial high priority activities here would be coordinating the improvements for the radars examined in Sec. IV. Because PMRT has already occurred for each radar, the role here would be one of coordination rather than direct management.

5. **Systems engineering and evaluation support**. Here there are two key activities. The first is to draw upon results from the Field Assessment area to evaluate the R&M situation with a subsystem of interest and share that evaluation with the cognizant program office. The second is to assure that adequate resources for systems engineering are applied to development of interface specifications whenever the Air Force takes on the responsibility for management of subsystem development.
6. **Improve test and evaluation resources**. As with the Technology Management area, to have the necessary test and evaluation resources adequately available may require special development and acquisition efforts. Electronic warfare and fighter fire control radar equipment are two classes of equipment in special need of such facilities.
7. **Coordinate technology management programs**. As with the other major areas, significant coordination of funds, priorities, and resources would be required.

Planning Area. The purpose of this last major area would be to develop plans for the Center based upon evolving projections of the threat, evolving assessments of field R&M deficiencies, and emerging technologies.

Prospective Benefit of an Avionics Engineering Center

A center formed along the lines of the preceding model would have the opportunity to:

- Sponsor advanced development of critical elements.
- Start FSED early for critical subsystems.
- Supervise maturational development for critical subsystems.
- Oversee post-PMRT maturation and engineering support.

Sponsor Advanced Development of Critical Elements. Just as the Engine SPO has sponsored advanced development of high-risk and technology-intensive components (such as gas turbine generators), so also could an Avionics Engineering Center sponsor advanced development of similarly complex and important equipment (major electronic assemblies, new architectures, digital communication protocols, etc.).

Start FSED Early for Critical Subsystems. Even with the benefit of advanced development of high-risk critical elements, some subsystems are sufficiently complex that they would also benefit from starting full-scale engineering development in advance of the airframe. Even the most sophisticated avionics equipment usually starts FSED after the airframe and engine. And once avionics FSED does start, it usually occurs without benefit of advanced development of its critical components. This practice made sense when combat airplanes consisted primarily of airframes and engines and when avionics equipment was added after designs had largely been completed. Now, however, avionics equipment plays a more central role in combat performance, and it accordingly overshadows most other equipment in cost, weight, volume, and complexity. It thus needs the early developmental attention customarily given airframes and engines.

Supervise Maturational Development for Critical Subsystems. The engine SPO already has a Component Improvement Program aimed at maturing engines. An Avionics Engineering Center should have similar responsibility not only for new avionics equipment but also for avionics equipment already in the field.

Oversee Post-PMRT Maturation and Engineering Support. An Avionics Engineering Center could be responsible for avionics subsystems both before and after PMRT. Such a practice would enable it to draw on information and experiences accumulated before PMRT to help oversee post-PMRT maturation and engineering support. In addition, so-called Avionics Technical Assistant Contractors could provide not only technical assistance to the Avionics Engineering Center but also a stable base for retaining corporate memory. To ensure objectivity, such contractors would have no contracts with the government to develop hardware or software. Technical Assistant Contractors have been used for years in the aerospace industry and more recently at the AFSC Armament Division at Eglin Air Force Base.

With the foregoing kinds of activities, an Air Force center of engineering excellence for avionics could lead the way in accelerating R&M-related avionics technologies (Proposal 1), improving the ability to test avionics equipment (Proposal 2), providing more complete feedback on equipment performance (Proposal 3), adopting a maintainability indicator (Proposal 4), and instituting maturational development (Proposal 5). The creation of an Avionics Engineering Center (Proposal 6) therefore is the linch pin for a cohesive strategy for reforming avionics acquisition and support.

VII. RECOMMENDATIONS AND CONCLUSIONS

RECOMMENDATIONS

The recommendations developed in Secs. III through VI are summarized here in the form of a set of related proposals that constitute a coherent strategy for reforming avionics acquisition and support. The strategy concentrates on the major weaknesses and the most promising solutions to these weaknesses that have come to our attention during 20 years of research in this field. The strategy is organized from the viewpoint that R&M is built upon multiple lines of defense that start with research on basic technologies and culminate with the maturation of specific subsystems and their support equipment.

Proposal 1: Accelerate R&M-Related Avionics Technologies

The first line of defense for R&M is for engineers to design it right from the outset. However, engineers' ability to do this is influenced greatly by the accumulated knowledge regarding the capabilities and limitations of the technologies used in a design. Unfortunately to deliver a subsystem design with the specified levels of functional performance, engineers often must apply the latest advances in technology. For emerging technologies that are critical to achieving mission essential performance, it is therefore essential to accumulate a body of engineering knowledge as rapidly and as efficiently as possible to form a solid basis from which design may proceed. The Air Force can help strengthen the engineering knowledge available to designers by accelerating the development of key avionics technologies. Certain technologies, moreover, promise especially important benefits to R&M. These need to be searched out and emphasized. To help do this, this proposal has three parts:

- Accelerate development of selected functional performance technologies.
- Accelerate research on failure pathologies.
- Accelerate research and development of Built-in Test technologies.

Although the Air Force already has efforts in each of these areas, there are opportunities to beneficially increase the level of those efforts.

Accelerate Development of Selected Functional Performance Technologies. Several avionics development efforts that are important to combat aircraft, such as fighters, will be entering full-scale engineering development during the next five to ten years. To more fully prepare for these important design efforts, the Air Force should review the current state of critical electronics technologies in search of opportunities to accelerate the pace of research and advanced development where appropriate.[1] Following such a review, the Air Force could reassess the adequacy of its investment in these areas and then tailor both the level and composition of its investments. Candidate technologies for accelerated research and development include:

- **Active Phased Array Technology.** Some new technologies promise to greatly improve R&M and thereby reduce the time and expense of a maturational development phase. One such technology for radars is an active phased array that can provide an electronically scanned antenna.
- **Gallium Arsenide Technology.** This technology promises to expand the analog processing capacity on board combat airplanes the way VHSIC is expected to revolutionize digital processing. Because this technology is a more recent development, engineering knowledge of this technology is still evolving.[2]

Accelerate Research on Failure Pathologies. During the next decade, the Air Force will use technologies like VHSIC to expand the functional capabilities of new and existing combat airplanes. The magnitude of this investment and the extent of this reliance on such technologies make it very worthwhile for the Air Force to aggressively sponsor research into the failure modes for these technologies.[3]

Accelerate Research and Development of Built-in Test Technologies. Here the Air Force has two especially important opportunities: improvement of methods and techniques and exploitation of VHSIC.

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[1]The Air Force could assess ways to accelerate development of avionics technologies to allow more time for learning about the conditions under which technology-peculiar faults will arise—both Type A and Type B faults. Such efforts would complement the maturational development process for the selected avionics equipment that undergoes the process and would also help improve the R&M characteristics of equipment not subjected to the maturational development process.

[2]At this point designers need a better engineering database to support the selection of operating temperatures that achieve appropriate balance between reliability benefits and design penalties in terms of the size, weight, and power required by the environmental control system.

[3]New technologies such as VHSIC and gallium arsenide circuits often raise great expectations about improved reliability and even about invulnerability to potentially serious failures. Time and again, development programs have fallen victim to what might be termed the "Titanic Syndrome." The Air Force can avoid catastrophic R&M "icebergs" only by improving our knowledge *in advance* about failure pathologies for critical new technologies.

- **Methods and Techniques.** An initial step could be the immediate launching of a special high-priority project to assess and accelerate the advancement of BIT technology. Such a project could
  - — Review current BIT mechanizations and catalog approaches, strengths, and weaknesses.
  - — Assess the major weaknesses in BIT technology and in contemporary applications of that technology.
  - — Develop a research plan to further the technology.
  - — Institute guidelines for testing BIT and for applying BIT technology during hardware and software design.
- **Exploitation of VHSIC.** VHSIC technology has considerable untapped potential for improving subsystem level BIT. Increased research in this area could pay large dividends.[4]

By selectively accelerating the advancement of key R&M-related technologies the Air Force can best strengthen the engineer's ability to design the equipment right from the outset. This is the first line of defense for R&M. However, even the best of designs will eventually develop faults during operational service. The second line of defense, comprehensive and accurate testing for faults, is the subject of the next proposal.

Proposal 2: Improve the Ability to Test Avionics Equipment

In the airplane, on the flightline, in the shop, and at the depot, the Air Force needs improved abilities to test avionics. Even with the best of efforts to accelerate the advancement and application of R&M technologies, faults will inevitably develop in avionics equipment. As a consequence, the ability to test and find faults is essential to maintaining designed capabilities.

Improve Ongoing Programs. To improve the testability of avionics equipment, the Air Force can place greater emphasis on improving fault-isolation capabilities in such research and development programs as Ultra-Reliable Equipment, Modular Avionics, and Avionics Integrity.

- **Ultra-Reliable Equipment Program.** Developing subsystems with ultra-high levels of reliability (2,000 to 10,000 hours between

[4]One promising idea that warrants increased attention is to use VHSIC to capture better information about the operating state and environment of avionics equipment when faults are detected.

failure) is desirable as long as the subsystems are practical.[5] However, projects exploring ways to build ultra-reliable equipment need to ensure that their labors do not ignore maintainability, especially because current fault-isolation systems fail to consistently identify the more difficult and more elusive Type B faults that plague current weapon systems.[6]

- **Modular Avionics Program.** The packaging of avionics equipment needs to be examined in light of the high costs of flightline replaceable units, some of which approach $1 million. One alternative currently drawing much interest would have flightline technicians remove modules—less expensive and about the same size as a current circuit card—directly from the airplane. This seemingly attractive idea may increase the likelihood of disrupting delicate connections. Moreover, because current BITs often cannot consistently isolate faults to specific LRUs (especially for Type B faults) research on modular avionics must place great emphasis on improving the fault-isolation capabilities of BITs.[7]
- **Avionics Integrity Program.** The Air Force has been considering a plan for an Avionics Integrity Program patterned after its Structural and Engine Integrity Programs. These programs aim at helping designers choose materials that avoid undue risks of catastrophic failures or unaffordable maintenance burdens. The Avionics Integrity Program can potentially help designers most by measuring thermal and dynamic stresses placed on electronic assemblies during routine operations, but it must not ignore improving fault-isolation capabilities in general and BIT capabilities in particular.

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[5]They must not become unaffordable, too large and too heavy for a combat airplane, too demanding in their cooling requirements, or too hard to fix when they fail. Some proponents believe that ultra-high levels of reliability (with fighter radars enjoying a 2000-hour mean time between confirmed failure) are both affordable and achievable given the current state of the art. Further, some believe that such reliability levels justify decreased emphasis on BIT. Others strongly disagree. Given the complexity of the equipment and the disagreement about realizable levels of reliability, the Air Force should strive for ultra-high reliability only to the extent that it does not short-change the maintainability that will be needed for realizable levels of reliability.

[6]There is a further concern that the trend toward micro-miniaturization may appreciably increase the density and number of pins on a typical circuit card. Such an outcome would further increase the risk of faulty connections that can be a source of Type B faults.

[7]There is disagreement about whether adequate BITs and sufficiently robust connections can be designed for the flightline environment. A shortfall in either area would adversely affect a fighter airplane that depends on quick isolation and corr ·ion of faults.

Improve Capabilities of Tests. For ground-based test equipment, the Air Force can improve the capabilities of tests by developing test translation dictionaries, direct entry into test sequences for specific sections of lengthy ground avionics tests, loop testing for specific tests, and special environmental and system bench capabilities for depots.

- **Test translation dictionaries.** Such dictionaries would enable avionics technicians at one maintenance level to translate test results from another maintenance level into terms they will find useful for isolating and correcting faults.
- **Direct entry into test sequences for specific sections of lengthy ground avionics tests.** Such direct entry would enable technicians to avoid having to run tests in an invariable, predetermined sequence. As a consequence, technicians would have greater ability to find Type B faults that are sensitive to time-varying thermal conditions.
- **Loop testing for specific tests.** Such loop testing would enable technicians to run the same test repeatedly. As a consequence, it improves the prospects of catching certain Type B faults.
- **Special environmental and system bench capabilities for depots.** Such capabilities would enable test equipment to better replicate operational modes and environmental settings that especially influence Type B faults.

Proposal 3: Provide More Complete Feedback on Equipment

Even with the best of test capabilities, some faults will inevitably escape detection by ground support equipment. Thus, R&M requires a third line of defense: Maintenance personnel need timely and reasonably complete feedback to deal quickly and effectively with faulty assets that escape repair.

To better provide such information, the Air Force can improve the quality of information received from the pilot's postflight debriefing to maintenance technicians, and it can improve the technicians' capability to track and identify hard-to-fix faults.

Improve Quality of Information Received by the Pilot Debriefing. The Air Force can explore improving the quality of pilot debriefings by using an automated system that would provide a menu of questions concerning airplane malfunctions. Such a system could use

- Data transfer units to capture information from the BIT.

- Personal computers to record information interactively from pilots.

These measures would help solve the very difficult problem of obtaining sufficient information about symptoms and operating conditions for Type B faults.

Improve the Tracking and Correction of R&M Deficiencies. To improve the tracking and correction of R&M deficiencies, the Air Force could institute a capability to do Performance Oriented Tracking of Equipment Repair (PORTER), an experimental prototype system using personal computers to track, identify, and help correct faulty equipment. PORTER aims at reducing avionics maintenance burdens, especially for sophisticated equipment such as fire control radars, through judicious collection and timely transmission of performance and maintenance information to critical points in the support process. This information should enable maintenance personnel to identify and more quickly fix equipment that otherwise would circulate repeatedly through the support process, using up time and scarce resources.

Proposal 4: Adopt a Maintainability Indicator

Even with the best of feedback to maintenance technicians about problems with equipment performance, R&M needs a fourth line of defense to attract needed management attention to resolve the more serious maintainability problems.[8] A single measure to indicate the overall maintainability of a subsystem and its associated ground support system would be desirable. Such an indicator could:

- Complement the existing reliability indicator (MTBF) and together with it provide a meaningful composite picture of equipment R&M.
- Be sensitive to the full range of problems that arise in identifying faults and isolating their causes.
- Account for all flights with indications of faulty subsystem operation.

The following proposed maintainability indicator is consistent with these principles:

[8]Such attention is essential to identifying and fixing the root causes of problems. It is also essential for effectively communicating maintainability problems to the research and development community. Such communication is essential to avoiding repetition of maintainability problems in the development of new equipment.

$$\text{Fault Removal Efficiency} = \frac{\text{MTBI}}{\text{MTBF}} \times 100\%$$

where MTBI = Mean flying Time Between flights with one or more Indications of faulty operation of the avionics subsystem.

MTBF = Mean flying Time Between flights with a shop confirmed Failure of the avionics subsystem.

A fault removal efficiency of 100 percent means that for every flight during which a subsystem manifested a symptom of degraded performance, technicians removed a fault from that subsystem before the next flight. A 25 percent efficiency means that an average of four flights with symptoms occurred before technicians removed a fault.

Proposal 5: Institute Maturational Development

Concept. Even with the best of implementations for the preceding proposals, some important R&M problems will inevitably evade early, satisfactory resolution, especially Type B faults in large, complex, and tightly integrated subsystems that incorporate many new technologies. Fire control radars for fighter airplanes fall in this category. Such subsystems and their associated ground support systems need a development phase to mature their R&M to the levels that will allow the subsystems to regularly deliver the full measure of performance for which they were designed. Such a maturational development phase needs two stages:

- **Stage 1 (Assessment):** Collection and analysis of engineering data while the subsystem is in normal use by the operator, followed by analysis of candidate improvements and formulation of a comprehensive package of improvements.[9]
- **Stage 2 (Implementation):** Implementation of the most cost-effective improvements that aim at regular delivery of full design performance.

Such a process offers a further line of defense that is needed to assure the delivery of necessary R&M characteristics for the most complex avionics subsystems and would be an important supplement to the measures suggested by the foregoing proposals.

[9]Areas of needed improvement may include airborne equipment, ground support equipment, hardware, software, and maintenance procedures.

Implementation. The Air Force can complete the implementation stage for ongoing efforts to mature the F-15 and F-16 radars, it can start data collection and analysis stages for selected other equipment, and it can institute a formally planned maturational development phase for avionics equipment on new airplanes:

- **Complete the Implementation Stage for Ongoing Efforts to Mature the F-15 and F-16 Radars.** The Air Force is demonstrating maturational development on the F-15C/D APG 63 and the F-16A/B APG 66 radars, as a result of the F-15/F-16 Radar R&M Improvement Program. Integrated sets of improvements have been defined, evaluated, and briefed by the cognizant Air Force organizations, including the Aeronautical Systems Division (ASD) Strike SPO that managed the radar contractors' efforts. Unfortunately, management responsibility for these improvements has since been diffused through many organizations. The Air Force's current challenges are (1) to continue its effective support for efforts to improve the R&M of the F-15 and F-16 radars and (2) to demonstrate its commitment both to maturational development as a concept and to R&M as a major goal.
- **Start Assessment Stage for Selected Other Equipment.** In addition to the F-15 C/D and F-16 A/B radars, other avionics equipment can derive comparable benefits from maturational development. This equipment includes radars (the APG 68 for the F-16 C/D, the APG 70 for the F-15E), ECM equipment, weapon delivery systems, and pods such as those forming the LANTIRN and targeting subsystem.[10]
- **Institute a Formally Planned Maturational Development Phase.** Because it costs extra money and runs the risk of creating undesirable publicity about R&M problems, some weapon system development programs may be reluctant to add a maturational development phase to their development efforts. To minimize such reluctance, a maturational development phase could be institutionalized as a formal and preplanned part of each program's management plan.

Maximizing the Benefit. Generally, maturational development will offer the greatest rewards for new equipment that enters development early enough to allow one or more follow-on development efforts for maturation prior to high-rate production. Such early application is

[10]These subsystems have been selected because they are nearly as complex as the two radars already subjected to the data collection and analysis process. Moreover, these subsystems, like the two radars, depend on leading edge technologies that may still be experiencing growing pains.

what we call *Approach A* to maturational development. It is the preferred approach in terms of maximizing the opportunity to avoid the high costs of retrofitting hardware. *Approach B* pertains to situations where avionics subsystems do not benefit from an early start to their full-scale engineering development. Opportunities for beneficial application of Approach B include situations where already fielded equipment

- And its associated support equipment are struggling to dependably deliver designed levels of mission essential performance because of R&M difficulties.
- And/or its support equipment are going to receive significant performance-oriented improvements.

Although Approach B may prove to be the predominant approach, experiences from the exploratory applications of maturational development have shown that there is considerable value to be gained by speeding up the acquisition and development process to start avionics development earlier. The typical late start leads to a hurried development effort that yields little time to explore the implications of using new technologies and materials.[11]

Late start and early termination of engineering are in turn compounded by transition of engineering management responsibilities from the SPO to the AFLC long before the equipment has matured. This transfer of engineering responsibility generally occurs during the equipment's early operational life, a time when engineers assigned to the SPO are only beginning to identify the equipment's strengths and weaknesses. Once the AFLC System Program Manager assumes responsibility, a new and much smaller group of Air Force engineers becomes responsible for the equipment's further maturation.[12] Moreover, with an impending transfer of R&M engineering responsibilities, it is hard to keep a development organization enthusiastically engaged in improving R&M. Such considerations support the idea of starting full-scale engineering development of avionics soon enough to allow time for the preponderance of maturation to occur before PMRT.

[11]This late start has been compounded by prematurely terminating the involvement of engineers. Even without the late start, merely the complexities of the equipment and its multi-layered support process guarantee that complex R&M problems will accompany the equipment when it enters operational service. At this juncture, an engineering database and analysis of the situation are critical to resolving dominant problems. Engineering involvement at this point has been far too shallow to build the kind of R&M database and associated analysis that the F-15/F-16 Radar R&M Improvement Program found so essential.

[12]In addition, these engineers must initiate entirely new contracting documents for any redesign work. This contracting procedure is far more burdensome than the one the SPO follows to accomplish the same sort of design changes before PMRT. Thus, any improvements in equipment maturation slow considerably after PMRT.

Even with an early start, the maturation process is costly and time consuming. Thus, a cost effective strategy for improving R&M must include additional lines of defense decreasing the problems that need to be cleaned up during a maturational development phase. To that end, the strategy's first four proposals aim to reduce the residual set of problems that would need to be addressed by maturational development (Proposal 5). The sixth and final proposal addresses an opportunity to amplify the benefits the Air Force can reap from the first five proposals.

Proposal 6: Reorganize Avionics Engineering Resources

For complex advanced technology subsystems, multiple lines of defense must be called upon to achieve needed levels of excellence in R&M. By reorganizing its avionics engineering resources the Air Force can better posture itself to coordinate defenses in a synergistically beneficial manner. R&M-related technologies (especially BIT technology) need to be advancing in support of development programs that improve test capabilities, while advances in performance-oriented tracking of equipment repair need to be coordinated to exploit improvements to the type of information that new test technologies and ongoing development programs can provide.

In contrast to such finely tuned coordination, past avionics research and development efforts have suffered from lack of (1) R&M guidance to laboratory projects, (2) a potent sponsor for the advanced development of critical elements, (3) an agency dedicated to supervising maturational development, and (4) an agency with a robust engineering organization overseeing post-PMRT maturation of both airborne and ground support equipment.

One way that the Air Force could address such deficiencies is to reorganize its avionics engineering resources in the form of what we call an Avionics Engineering Center. Such a center would *help*[13] oversee research, development, and maturation of sophisticated avionics subsystems (fire control radars, electronic warfare systems, and the like) by

1. **Sponsoring Advanced Development of Critical Elements.** An Avionics Engineering Center could sponsor advanced development of complex and important equipment (such as major electronic assemblies, new architectures, and digital communication protocols).

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[13]Primary responsibility for managing subsystem development may reside with a weapon system's prime contractor, *or* its System Program Office *or* an Avionics Engineering Center. In the first two situations, the role of the Center would be to assist the cognizant SPO.

2. **Starting FSED Early for Critical Subsystems.** Even with the benefit of advanced development of high-risk critical elements, some subsystems are sufficiently complex that they would also benefit from starting FSED in advance of the airframe.
3. **Supervising Maturational Development for Critical Subsystems.** An Avionics Engineering Center could have responsibility not only for selected new avionics equipment but also for selected avionics equipment already in the field.[14]
4. **Overseeing Post-PMRT Maturation and Engineering Support.** An Avionics Engineering Center could be responsible for avionics subsystems both before and after PMRT. In addition, avionics technical assistant contractors could provide not only technical assistance to the Avionics Engineering Center but also a stable base for retaining corporate memory.

In the past there has been resistance to such concepts as an Avionics Engineering Center and subsystem-focused maturational development. Commonly cited reasons include concerns about the adequacy of the Air Force's resources that could be allocated to managing subsystem development and maturation, especially in areas with complex interfaces. Other concerns are based upon fears that the application of technological advances may be retarded and the prime contractors' ability to optimize a weapon system may be seriously constrained. Against such concerns the Air Force needs to weigh two considerations. First is the relationship between past practices and current difficulties with avionics R&M. Second is the new challenges that will flow from the rapidly changing character of avionics technology.

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[14]To ensure objective management of such an effort, the group that manages the data assessment effort could be independent of the group responsible for the subsystem's development. While independent, both groups could reside within an Avionics Engineering Center or within a weapon system SPO. In the case of the Radar R&M Program, such independence proved very beneficial. Although certain tensions were created, they stimulated creativity and sharpened a focus on important problems and critical uncertainties. Such a center could also help in preplanning, which is another key to formalizing the maturation process. Certain types of equipment have a high enough likelihood of benefiting from the process that the program management plan for development could beneficially specify time and funds for the Stage 1 assessment effort. Such an up-front commitment could save time and funds. Up to two-thirds of the cost for implementing the R&M improvements for the F-15 C/D radar and the F-16 A/B radar probably could have been avoided by promptly executing such an R&M maturation process immediately upon the equipment's entry into operational service.

CONCLUSIONS

For its combat airplanes to meet and defeat future threats, the Air Force's avionics subsystems will continue to grow in terms of functions, sophistication, and complexity, while relying heavily on the latest advances in technology. To meet the challenge of acquiring and supporting the full designed capabilities of such equipment, the Air Force needs to aspire to high levels of excellence in avionics R&M. The Air Force would benefit from the improved coordination that an Avionics Engineering Center could provide to managing multiple lines of defense. Such a center could cap a major reform built upon four cornerstone concepts:

- Explicit recognition of Type B faults.
- Implementation of PORTER to more rapidly identify Type B problems.
- Use of fault removal efficiency as a management indicator for maintainability.
- Institutionalization of maturational development as a last line of defense for R&M.

Although any of these concepts would prove beneficial, the complete strategy would constitute a major reform to how the Air Force acquires and supports avionics. With such reform, the Air Force could exploit rapidly advancing electronics technologies to achieve levels of excellence in avionics that would ensure the superiority of its combat airplanes.

Appendix A

PRELIMINARY ASSESSMENT OF AVIONICS MATURITY

This appendix describes a preliminary assessment of avionics maturity conducted by RAND in 1980 using the Air Force's standard data sources for the F-15 and F-16. Although these data are not new, they illustrate the limitations of standard data collection systems, and conclusions about avionics maturity drawn from them have been largely substantiated by the subsequent special data collection efforts described in the text.

LIMITATIONS OF STANDARD DATA COLLECTION SYSTEMS

The Air Force's standard data collection systems have a limited ability to provide conclusive and in-depth views of the nature of potential avionics R&M problems and the extent to which these problems may cause the avionics equipment, and hence the aircraft, to deviate from its designed level of performance.

The standard data collection systems can best deal with Type A faults, where symptoms are observable no matter who examines the equipment and no matter where the examination occurs. However, many of our avionics R&M problems result from Type B faults, where symptoms do not always repeat and are hard to pin down. Such faults play havoc with attempts to develop, operate, and support sophisticated avionics equipment.

Although standard data collection systems collected data throughout and subsequent to the entire development and production process for the F-15 and F-16, these data failed to identify many of the Type B faults that were discovered in our subsequent special data collection efforts (described in Sec. IV).

Even by 1980—over four years after the F-15 had achieved IOC and over one year after the F-16 had achieved IOC—no clear picture had evolved concerning whether avionics for these aircraft had matured to the point of regularly delivering their full designed levels of performance.

Data collected during 1980 concentrate on the number of LRUs sent to avionics automatic test stations per flight flown, automatic rather than manual test stations because these LRUs tend to be the more sophisticated, more costly, and more troublesome ones that are essential to the F-15's combat effectiveness.

The most accurate source of data on these LRUs proved to be the manual forms maintained by shop technicians.[1] Because we had to review forms for each LRU serial number, we limited our inquiry to the more sophisticated LRU types processed by the automatic test equipment.[2]

Data from the manual forms proved much more accurate than data collected by the Air Force's computerized maintenance data collection system (known as MDC or AFTO 349).[3] Discussions with shop and flightline maintenance personnel elicited the following plausible explanations:

- The shop uses manual forms (instead of the AFTO 349 Form for computerized documentation) to document specific LRUs that repeatedly visit the shop for no apparent reason. Shop personnel place highest priority on these manual forms because they can send an LRU to the depot after it has visited the shop three or four times.
- The AFTO 349 Form appears unsuited to the realities of avionics maintenance. It relies on a lengthy list of codes to characterize malfunctions and actions taken, and it fails to capture the kind of information that maintenance personnel need to do their jobs. The AFTO 349 Form is particularly unsuited to documenting the swapping of electronic components that inevitably occurs on the flightline and in the avionics shop as a last-ditch means of isolating faults in avionics and test equipment. Consequently, separate manual devices, such as the shop's LRU form and log books on the flightline and in the shop, are widely used.

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[1] Air Force Technical Order Form 95.

[2] Today, at Bitburg Air Base, such information is routinely being entered into PORTER.

[3] Air Force Technical Order Form 349 provides the input for the Maintenance Data Collection (MDC) System.

PRELIMINARY ASSESSMENT OF AVIONICS MATURITY FOR THE F-15

Experiences of F-15s in the 49th TFW at Holloman AFB in 1980 strongly suggested areas where improved maturity of avionics subsystems and associated support resources could considerably increase the regular delivery of full designed performance. During May, June, and July, specialists removed 660 LRUs and sent them to the avionics shop's automatic test stations.[4] These airplanes averaged one such removal for each five flights flown. During this 90-day period, 250 of the 660 LRUs sent to automatic test stations were "reoccurrences": The flightline specialists had already removed the same LRU type at least once from the same airplane during the 90-day period.[5]

Figure A.1 groups these 68 F-15s into quartiles according to the frequency with which flightline specialists sent LRUs from each airplane to automatic test stations. Airplanes in the third quartile, flying 27 percent of the wing's flights, experienced 35 percent of the wing's removals, with roughly one occurring for every five flights. Airplanes in the fourth quartile, flying only 11 percent of the wing's flights, experienced 38 percent of its removals, with one occurring for less than every two flights. Taken together, data on the 34 airplanes in these two quartiles indicate that half of the wing's airplanes averaged almost one removal for every three flights. Moreover, during this 90-day period, nearly half of the LRUs sent to automatic test stations from these 34 F-15s were reoccurring removals.

A look at the histories of some particularly troublesome airplanes helps identify the avionics subsystems where improved maturity could increase the dependable delivery of full designed capabilities. Three F-15s—airplanes 7133, 7109, and 7153—accounted for 41 of the 250 reoccurring removals.

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[4]They also sent a comparable quantity of other LRUs to the manual test stations. Automatic stations test 44 LRU types, manual stations 56 types. Excluded from our assessment are four F-15s that hardly flew during this period. As this report is being published some seven years after these data were collected, the overall level of maintenance activity remains roughly the same, although it does vary from base to base and over time at a given base.

[5]We use the term "reoccurring" to avoid confusion with "recurrent," which the Air Force uses to indicate a removal that recurs within three flights, and "repeat," which the Air Force uses to indicate a removal that repeats after the next flight. These 250 reoccurring removals seem excessive for so short a time. If we take the most frequently removed LRU type (1.7 removals per 100 flights) and the most frequently flying of these airplanes (65 flights during the 90-day period), we should expect only 1.1 removals for the most frequently removed LRU type. To assess the chances that these reoccurring removals were the result of a simple random process, we statistically tested the hypothesis that these reoccurring removals could be explained as the outcome of a simple Poisson arrival process. The chance of that hypothesis being true turned out to be less than 1 in 200.

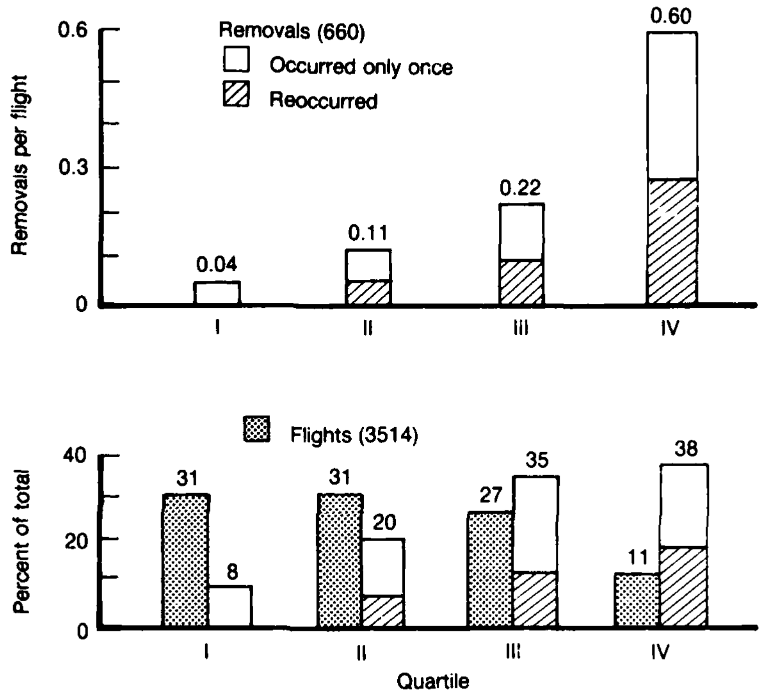

Fig. A.1—LRU removals, by quartile, for the 49th TFW (June through July 1980)

Falling in the third quartile with 49 percent of its wing experiencing more LRUs removed per flight, Airplane 7133 had—as Fig. A.2 shows—roughly one removal for each six flights flown. Its removals occurred in the head-up display, navigation, and radar subsystems.

Perhaps most important are this airplane's experiences with its navigation and radar subsystems. Without them, the F-15 can fly but it cannot carry out its unique combat responsibilities. In the navigation subsystem, flightline specialists removed and replaced the inertial measurement unit three times; in the radar subsystem, they removed and replaced the receiver three times and the analog processor four times. These experiences indicate more than a frequent removal and replacement of LRUs: They suggest that during the month of June, while the airplane was flying 29 times, it probably lacked a dependable fire control radar.

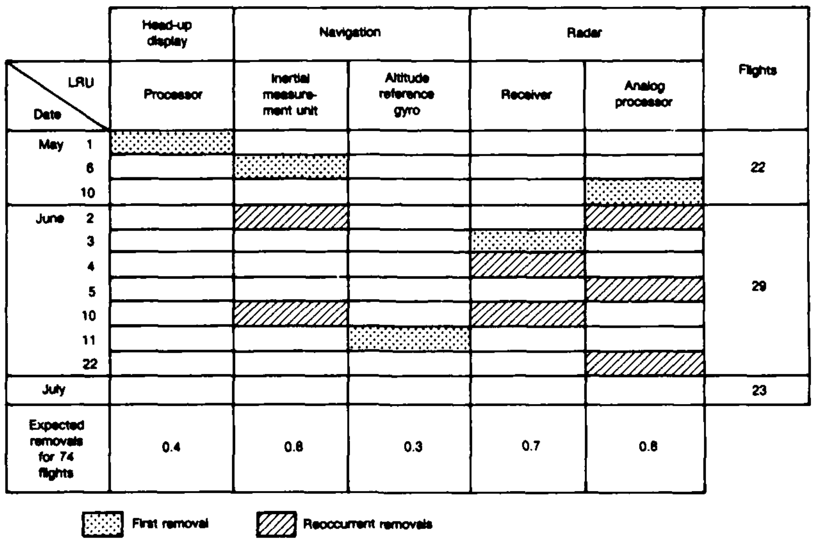

Fig. A.2—LRU removals from F-15 number 7133
(June through July 1980)

Falling in the fourth quartile with respectively 16 and '0 percent of their wing having more LRUs removed per flight, Airplanes 7109 and 7153 had even more frequent removals. As Figs. A.3 and A.4 show, Airplane 7109 experienced roughly one removal for each two flights and Airplane 7153 one for each flight. Their removals occurred in the flight controls, inertial navigation, head-up display, radar, and instruments.

Although removals appear over a broad spectrum, they seem to concentrate in these airplanes' radar and for Airplane 7153 in its inertial navigation subsystem as well. These particular removals suggest that Airplane 7109 probably lacked dependable combat avionics equipment for three months, during which it flew 40 times, and that Airplane 7153 probably lacked it for two months, during which it flew 29 times. In addition, the histories of these airplanes suggest that flightline specialists often could not identify malfunctioning LRUs. We see their frustration over being unable to isolate faults when on June 11 they removed a total of four LRUs from Airplane 7103, and on July 14 they removed a total of five from Airplane 7153, in both cases without seeming to solve the problem.

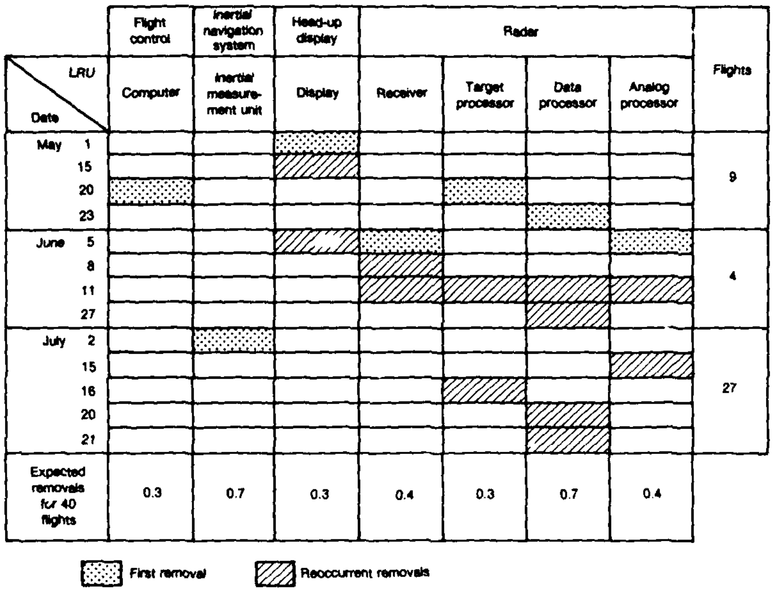

Fig. A.3—LRU removals from F-15 number 7109
(May through July 1980)

PRELIMINARY ASSESSMENT OF AVIONICS MATURITY FOR THE F-16

Experiences of F-16s in the 388th TFW at Hill AFB in 1980 also strongly suggested areas where improved maturity of avionics subsystems and associated support resources could considerably increase the regular delivery of full designed performance. During September, October, and November 1980, 104 of its F-16s flew 4363 times, and flightline specialists removed 799 LRUs that could be tested by the F-16's automatic test stations.[6] These airplanes averaged one such removal for each five flights. During this 90-day period, of the 799 LRUs sent to the automatic test stations, 168 were reoccurring removals. Although repair records for these airplanes show fewer reoccurring removals than those experienced by F-15s, this situation may change once the wiring and connecters on F-16s accrue a comparable amount of service time.

[6]Automatic stations can test 50 LRU types although the Air Force has chosen to test only 37 of them at the airbase level. Statistics on the F-16 are computed on the basis of these 50 LRU types.

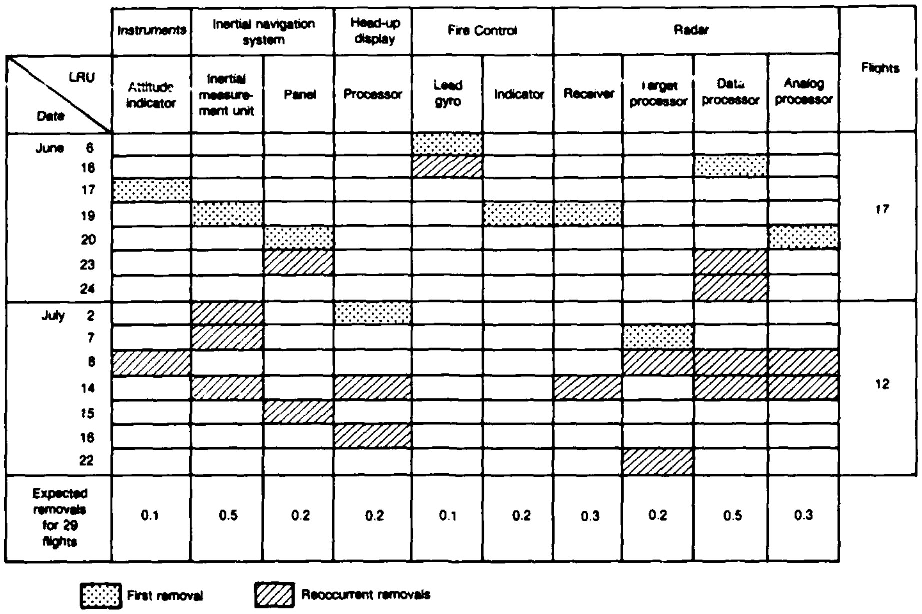

Fig. A.4—LRU removals from F-15 number 7153
(June through July 1980)

Figure A.5 groups these 104 F-16s into quartiles according to the frequency with which flightline specialists sent LRUs from each airplane to automatic test stations. Airplanes in the last quartile, flying 22 percent of the wing's flights, experienced 44 percent of the wing's removals, with one occurring for less than every three flights. Moreover, during this 90-day period, roughly one-fourth of the LRUs sent to automatic test stations from these 26 F-16s were reoccurring removals.

Again, a look at the histories of some particularly troublesome airplanes helps identify the avionics subsystems where improved maturity could increase the dependable delivery of full designed capabilities. Three F-16s—Airplanes 0079, 0021, and 0086—accounted for 22 of the 168 reoccurring removals.

Falling in the fourth quartile with 22 percent of its wing experiencing more LRUs removed per flight, as Fig. A.6 shows, Airplane 0079 had roughly one removal for each three flights. Its removals occurred in the flight controls, flight control instruments, communications, and radar subsystems.

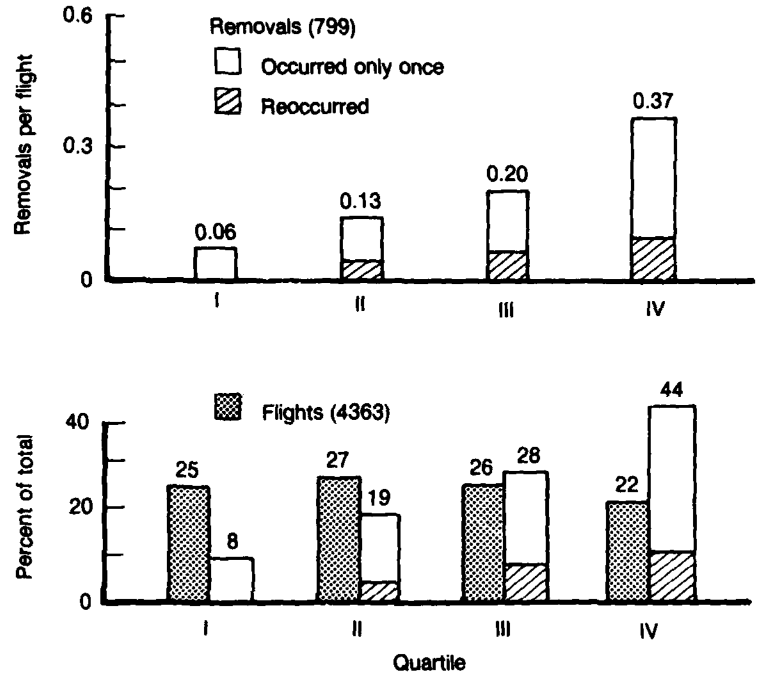

Fig. A.5—LRU removals, by quartile, for the 388th TFW (September through November 1980)

Here removals appear over a broad spectrum of subsystems, although most occur in the flight controls and flight control instruments. Flightline specialists on October 26 removed the air data computer; two days later they again removed the air data computer, this time with the electronic component assembly; two days later they once again removed the electronic component assembly.

Falling in the fourth quartile with 16 and 15 percent respectively of their wing having more LRUs removed per flight, Airplanes 0021 and 0068 had even more frequent removals. As Figs. A.7 and A.8 show, both airplanes experienced roughly one removal for each three flights. Their removals occurred in the flight controls, instruments, radar, head-up display, fire control navigation, electrical optical display, stores management set, and threat warning subsystems.

Although removals again appear over a broad spectrum, they seem to concentrate in the radar subsystem on Airplane 0021 and in the fire

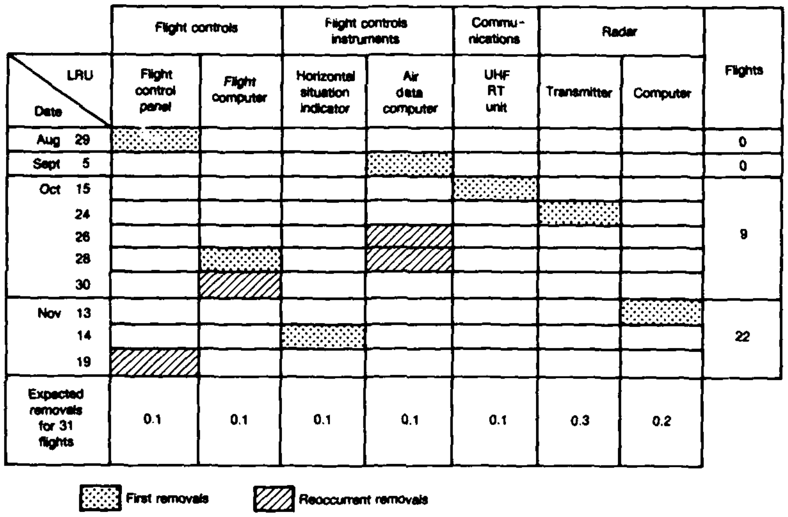

Fig. A.6—LRU removals from F-16 number 0079
(September through November 1980)

control navigation and threat warning subsystems on Airplane 0086. These particular removals suggest that Airplane 0021 probably lacked dependable combat avionics equipment for three months, during which it flew 50 times, and that Airplane 0086 probably lacked full combat effectiveness for more than two months, during which it flew 38 times. The history of Airplane 0021 also suggests that flightline specialists often could not identify its malfunctioning LRUs. On September 16 they removed a total of five of its LRUs, four of which come from the radar, without seeming to solve the problem.

The quartile analyses for the F-15 and the F-16 reveal very broad distributions in terms of removals per flight. Reoccurring removals tend to happen far more often with fourth quartile airplanes than with first quartile airplanes. Because fault isolation problems give rise to reoccurring removals, the quartile analyses show the extent to which such maintainability problems are degrading the condition of certain airplanes.

Causes of Frequent and Reoccurring Removals of LRUs

Do the frequent and reoccurring removals of LRUs result from the immaturity of the LRUs and the test equipment, or from the overwill-

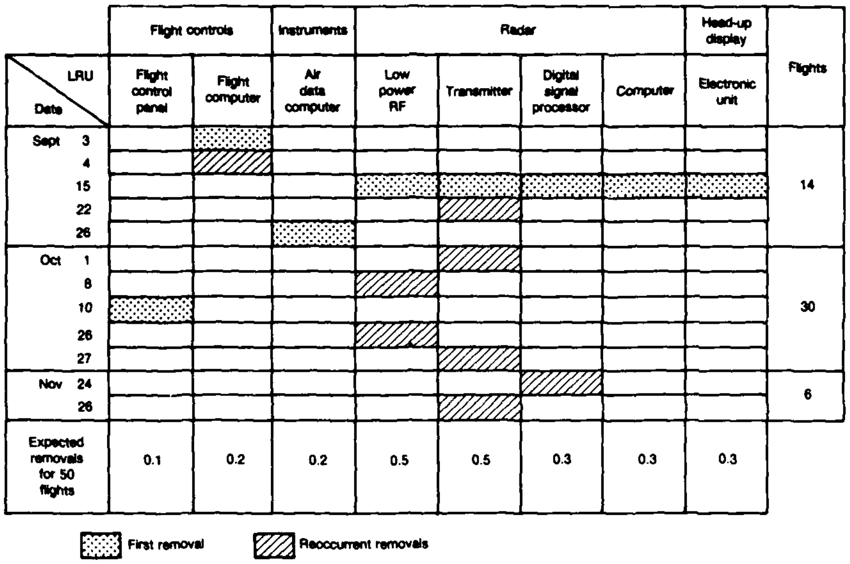

Fig. A.7—LRU removals from F-16 number 0021
(September through November 1980)

ingness of flightline specialists to remove apparently troublesome LRUs from airplanes?[7]

Our research in 1980 suggested that flightline specialists do not remove excessive numbers of LRUs. For example, Fig. A.9 shows that F-16 Number 0021 reported on 14 occasions between September 1 and November 30, 1980 that it experienced problems with its radar. Two of these reports were "Code 3," meaning that the flightline should immediately correct problems; 12 were "Code 2," meaning that they could delay corrective action. Such reports indicate two things about these codes:

1. Many peacetime Code 2 reports would be Code 3 reports in wartime because pilots could not tolerate degraded radar subsystems during combat.

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[7]In F-15s and F-16s, the flightline specialists cannot repair LRUs, they can merely send them to the avionics shops.

2. Flightline specialists do not always respond immediately to Code 3 reports: this airplane had to fly seven missions between its initial Code 3 report on September 16 and the removal of a radar LRU on September 22.

In spite of the total of 14 reports, flightline specialists removed a radar LRU on only six occasions, forcing the airplane to fly at least 67 flights between reporting a faulty radar and having a radar LRU removed. Overall, in 1980 we found that flightline specialists receive roughly twice as many complaints as they remove LRUs.

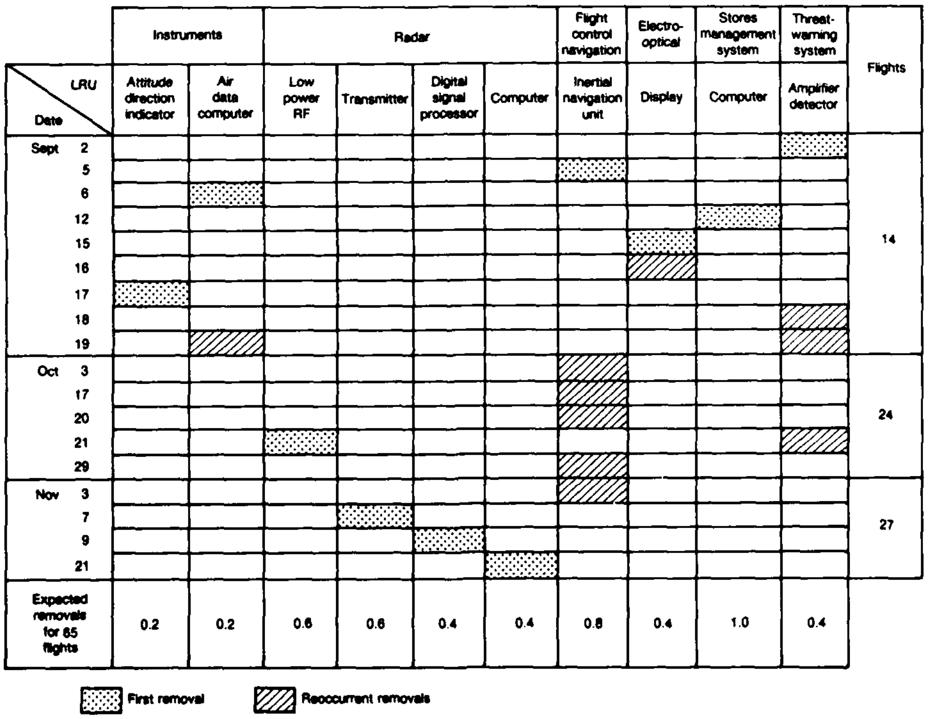

Fig. A.8—LRU removals from F-16 number 0086 (September through November 1980)

Date	Landing Code	Pilot's Report	Flights Between Report and Removal	Date LRU Removed
9/16	3	Rdr inop. antenna vibrates a/c	7	
9/17	2	Rdr on — antenna causes vibration	6	
9/22	3	Rdr w/n transmit — MFL 1 010	1	9/22
9/23	2	Rdr MFL 10109038.3 w/n lock on	2	
9/25	2	Rdr antenna vibrates when on	1	
9/25	2	Rdr 1 010 6 46 transmitter quit	0	10/1
10/2	2	Rdr w/n lock on	5	10/8
10/9	2	Rdr 6 350 3 125.9 hard fail 3 BITS	16	
10/9	2	Rdr inop 10101036.6 60027039.9	14	
10/16	2	Rdr 6 480 1 4.3 Rdr vibrates	11	
10/24	2	Rdr inop MFL 10109 31.8	2	10/26
10/27	2	Rdr inop 1 010 9 56.9	1	10/27
11/6	2	Rdr MFL 6480 1 2.8 1010 2 70.2 Antenna knob sticks in detent	1	11/24
11/28	2	Rdr detent sets 10 deg low Rdr antenna vibrates	?	

Fig. A.9—Radar discrepancies reported against F-16 number 0021 (September through November 1980)

LIMITATIONS OF THE 1980 DATA COLLECTION AND ANALYSIS

The 1980 data collection and analysis efforts are potentially limited by the inferential nature of the analysis and the dependability of the data.

The Inferential Nature of the Analysis. The analysis inferred that the removal of an LRU meant that a fault was present and that the repeated removals of LRUs meant that one or more faults remained throughout the period of reoccurring removals. Although interviews with pilots, maintenance personnel, and contractor field representatives corroborated the general reasonableness of these inferences, they also pointed out that pilots occasionally request maintenance when none is warranted, and technicians occasionally remove LRUs when there are no defects.[8] Because of the complex nature of

[8] Flightline maintenance personnel, pilots, and experienced contractor engineering representatives all recount anecdotes about the other two who do not seem to understand the equipment.

fire control radars and because radar performance can be influenced by factors external to the aircraft, there is no way of knowing how often such mistakes occur.

The Dependability of the Data. Rapid preparation of aircraft for scheduled flights is the main concern of flightline maintenance units. Accurate documentation is not. As a consequence, maintenance documentation does not always accurately record the airplane number from which an LRU was removed. In addition, maintenance personnel may swap LRUs between airplanes to facilitate the fault-isolation process. Thus, maintenance documentation may record the last airplane the LRU was tried in on the ground rather than the airplane in which it actually flew.

Appendix B

BACKGROUND FOR EXPLORATORY APPLICATIONS OF MATURATIONAL DEVELOPMENT TO THE F-15 AND F-16 RADARS

The preliminary assessment of avionics maturity described in Appendix A prompted the Directorate for Plans at the Air Force Systems Command (AFSC) to ask RAND to define and help implement a demonstration program for maturational development. The program concept, first briefed during September 1980, was subsequently briefed to the Air Staff during June 1981. The proposed plan called for a two-stage demonstration program involving

- Stage 1: Data collection and analysis (including definition of promising candidates for improvement).
- Stage 2: Implementation of the most cost-effective R&M improvement options.

As requested by AFSC, the plan concentrated on the Westinghouse APG-66 block 15 radar used on the General Dynamics F-16 A/B aircraft and the Hughes APG-63 radar used on the McDonnell F-15C/D aircraft.

According to the plan, Stage 1 would consist of six-month data collection and analysis efforts at Hahn Air Base and Hill AFB for the F-16 and at Bitburg Air Base and Langley AFB for the F-15. These efforts would be conducted at each base by teams of approximately 15 engineers or technicians contracted directly by the government and supplied by the radar contractors and the aircraft prime contractors. These teams would

- Conduct post-flight debriefings of pilots after their normal maintenance debriefings to assess how well the radar operated.
- Observe and document—but not interfere with—maintenance actions on the flightline and in the avionics shop.
- Collect information on maintenance actions taken at the Ogden depot for the F-16 and at the Warner Robins depot for the F-15.
- Analyze the effectiveness of maintenance actions by examining pilot inputs for flights that followed the completion of maintenance actions.
- Analyze the causes of ineffective maintenance actions and propose appropriate remedies.

Three types of concerns delayed implementation of this plan:

1. The depots already had many unfunded opportunities to improve R&M.
2. The Air Force already had a vast maintenance data collection system that was underutilized and was being ignored by Stage 1 efforts.
3. The cost of collecting data would exceed the cost of implementing some of the already identified R&M improvements.

Because of these concerns, the Air Staff asked the ASD Strike SPO to coordinate meetings that included the cognizant depots and SPOs and that examined the need for the proposed special data collection efforts for the F-16 and F-15 radars. By June 1982, these meetings had established that the Air Force's standard data could not be used to assess radar R&M problems *and* determine their causes.

Upon receiving this assessment from the ASD Strike SPO, the Air Staff began preparing program direction to collect appropriate R&M data for the F-16 and F-15 radars. This direction was formalized in a Program Management Direction (PMD) sent to AFSC during December 1982. The AFSC subsequently assigned responsibility for this PMD to the ASD Strike SPO.

Following a series of meetings with the cognizant depots, SPOs, and ASD organizations, the Strike SPO determined that the "appropriate data collection efforts" should have the approximate magnitude that RAND had proposed in its Stage 1 specifications. Accordingly, the ASD Strike SPO in September 1983 issued a Request for Proposals that included most of these specifications.

The resulting F-15/F-16 Radar R&M Program began its six-month data collection efforts during June 1984. The results of the contractors' engineering analyses were presented to the Air Force during May 1985, and the ASD briefing of the contractors' analyses was presented to the Air Staff during September 1985. At that time, the Air Staff formed an ad hoc team to prepare plans for Stage 2 attempts to improve the R&M for the F-16 and F-15 radars.

BIBLIOGRAPHY

Gebman, J. R., H. L. Shulman, with C. L. Batten, *A Strategy for Reforming Avionics Acquisition and Support: Executive Summary,* The RAND Corporation, R-2908/1-AF, July 1988.

McIver, D. W., A. I. Robinson, and H. L. Shulman, with W. H. Ware, *Proposed Strategy for the Acquisition of Avionics Equipment,* The RAND Corporation, R-1499-PR, December 1974.

Meyer, D. G., and B. F. Schemmer, "An Exclusive AFJ Interview with General Lawrence A. Skantze, USAF," *Armed Forced Journal International,* September 1985, p. 64.

Nelson, J. R., P. Konoske Dey, M. R. Fiorello, J. R. Gebman, G. K. Smith, A. Sweetland, *A Weapon-System Life-Cycle Overview: The A-7D Experience,* The RAND Corporation, R-1452-PR, October 1974.

Petruschell, R. L., G. K. Smith, and T. F. Kirkwood, *Using the Air Force Maintenance Data Collection System Data to Identify Candidates for Improvement in Reliability and Maintainability,* The RAND Corporation, N-2549-AF, March 1987.

Rich, M. D., E. Dews, with C. L. Batten, *Improving the Military Acquisition Process: Lessons from RAND Research,* The RAND Corporation, R-3373-AF/RC, February 1986.

Rich, M. D., W. Stanley, and S. Anderson, *Improving Air Force Readiness and Sustainability,* The RAND Corporation, R-3113/1-AF, April 1984.

Robinson, A. I., and H. L. Shulman, *Experience with Air Force Inertial Navigation Systems: Some Effects of Research, Development, Procurement, and Support Policies on Life Cycle Costs,* The RAND Corporation, R-892-PR, February 1972.

Robinson, A. I., and H. L. Shulman, *Comparison of Repair Operations: Newark Air Force Station and Industry,* The RAND Corporation, RM-5397-PR, September 1967.

Soviet Military Power, 1985, U.S. Department of Defense, Washington, D.C., April 1985.

Stanley, W. L., and J. L. Birkler, *Improving Operational Suitability Through Better Requirements and Testing,* The RAND Corporation, R-3333-AF, November 1986.

Stucker, J. P., and G. K. Smith, *Warranties for Weapons: Theory and Initial Assessment,* The RAND Corporation, N-2479-AF, April 1987.

U.S. Department of Defense, *Soviet Military Power, 1985,* Washington, D.C., April 1985.